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ESTIMATING TIDAL ENERGY RESOURCE POTENTIAL FOR POWER PRODUCTION ALONG KENYAN COAST-LINE

BY

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DEDICATION

All honor to you Almighty God for creation and destiny are your act.

I, dedicate this thesis to my father,

The Late Mwalimu James Ayako Wakah

Dad, I missed a precious opportunity,

'To Listen to Your Dream'

Rest in Peace, Dad

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PREFACE

This thesis was prepared by me, Lucy Patricia Onundo in consultation with Dr. Wilfred Njoroge Mwema, and Dr. Cyrus Wekesa Wabuge from University of Nairobi, Department of Electrical and Information Engineering, Nairobi, Kenya in my pursuit for acquisition of Master of Science Degree in Electrical and Electronic Engineering.

A summary and synthesis of the wealth of information on oceanography, hydrodynamics and hydraulics in relation to ocean energy was acquired from 2013 and compiled in this thesis to stimulate further study and research. The research explored ocean water properties, topography and energy productivity.

Modeling and analysis of the performance of tidal-stream energy resource equipment displayed the need to estimate equivalent electrical power extracted. Unlike other clean energy sources, the time and magnitude characteristics of tidal energy can be predicted. Negligible resource assessment had been previously documented on tides and tidal energy sites along the Kenyan coastline to draw credible implementation directives.

The problem was to predict the electrical power output and analyze the economics behind installation of tidal stream device from a daily tidal cycle to one year or more. The result was a flow that accelerates from rest to speeds in excess of 3m/s before peaking, reversing, accelerating and decelerating in the opposite direction. Turbulence effects on daily or twice-daily pattern generate peak flows and outputs that are significantly larger than the mean. There are variations from the seabed to the surface. The flow peaks just below the surface and decelerate as the seabed is approached. The rate of deceleration depends upon both the overall flow velocity and the seabed nature. The magnitude of the flow increase and decrease over the lunar cycle, peak a few days after new and full moons and increase still further around the equinoxes in March and September. The device type, its efficiency in converting flow energy into rotary motion then to electrical power in addition to the overall construction and operational maintenance cost, determined the tidal estimate.

We hope from different contributors that a clearer derivation of the scientific principles emerge in a bid to realize development progress.

ABSTRACT

Kenyan fast economic progress evident by a population ranked at third highest growth rate in Sub-Saharan Africa as per World Bank 2015 should invest in infrastructure. The industrialization (oil and gas discoveries), transport (standard gauge railway), international grid networks and increased employment opportunities, calls for expansion of electrical energy sources to meet the current and future demand. Unfortunately, the mature fossil fuels energy supplies have caused environmental crisis evident by climate change and climate variability, as a result of global warming due to temperature effects and air pollution. In 2008, Kenya Vision 2030 strong environmental policies and regulations targets were set towards reduction of greenhouse gas emissions and significant renewable energy improvement by driving a low carbon economy.

The rapid depletion of fossil fuel reserves and their dire influence on global policy precipitated to inflated energy costs due to disruptive repercussions that affect trade balance and negative emissions effect. The Kenyan reserves status may change with the recent Tullow oil discoveries in March 2016. Diverse energy sources with emphasis on renewable energy investments as per European Commission's 2011 Energy strategy roadmap 2050 are essential and urgent to improve security of energy supplies. This advocates for an alternative exploration of safe, reliable, quality, competitive and affordable energy for all consumers.

The thesis examined marine tidal stream resource potential for renewable energy generation using computational hydrodynamic models, i.e. Matlab and excel. The assessment entailed resource characteristics, converter device performance and renewable energy yield predicted. The geographical focus was Mombasa, Lamu, supported by published reports on exploitable tidal stream energy resources, and the deployment technology. The thesis presented applied theoretical calculations and numerical simulations to estimate not only the power to be extracted from the flow through a passage, but also reduction in passage flow. The analysis took into account physical and environmental constraints to quantify the untapped tidal stream electrical power potential in Kenya, along the Indian Ocean.

Kenya's effective grid connected electricity capacity currently is at 3000 MW as at March 2015, with a strategic target to increase beyond 5000 MW by 2016. In accordance to the theoretical calculations and simulations, an estimate of 1.9 GW (16.5 TW/h per annum) of tides and tidal power can be extracted averaged across the fortnightly tidal cycle whose resource potential can be higher with deployment. The tidal stream energy resources in Kenya are abundant for electricity extraction with proper site planning and optimization of the ocean energy converters. Characterization, mapping and tapping of the tidal resource reduce uncertainties thus increase and advance investment value of the current green energy initiative. The estimated global potential of tidal stream energy is agreed to exceed 120 GW (1053 TW/h per annum) with negligible investment in Africa and India as per Ocean Energy Europe, 2017.

Significant upstream and downstream effects of energy extraction on velocity and elevation in a channel set-up extended to a sigma layer model of the hydrostatic primitive equations. Simulations demonstrated the limits within which the blocking effect of a tidal farm was of significance regarding the change to the hydrodynamic regime brought about by extensive energy extraction and potential redistribution of tidal currents away from the installed device(s) location.

Although the assessment outcome points out that Mombasa and Lamu tides and tidal energy resources are viable for exploitation, inherent shortcomings exists on high capital costs, political instability, annual reliable energy density, technology level upgrade and human capacity competence. The current estimated costs are higher than the existing energy systems, a measure which can be addressed to technically contribute strategically in the formulation of necessary policies and networks to realize the overall ocean energy potential and promotion.

Keywords:

Marine tidal power, MATLAB/Simulink energy optimization model, renewable energy

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NOMENCLATURE

LIST OF TERMS AND SYMBOLS

For the purposes of this document, the following terms, descriptions and symbols apply.

SYMBOL	DESCRIPTION
F_G	Tide generating force Newton, N
G	Universal gravitational constant ($6.673x10^{-11}$ Nm^2/kg^2)
M	Fluid mass flow Kilogram, kg
$m_1\, m_2$	respective masses of an object (earth, sun or moon), kg
r	distance between centres of objects (meter, m)
L	Characteristic length equal to diameter if cross-section is circular (meter, m)
Ƞ	Surface elevation, (meter, m)
P	Fluid density (kg/m^3)
A_C	Cross sectional area of the channel, m^2
A_T	Turbine rotor swept cross sectional area, m^2
T	Internal torque induce shear stress $\propto$ angle of twist
μ	Coefficient of viscosity $\left(\frac{kg}{ms}\right)$
ν	Kinematic fluid viscosity $\nu = \frac{\mu}{\rho}$, m^2/s or 1 Stoke (St.) $=1cm^2/s$
P_E	Kinetic power, joule per second J/s or watt, W
P	Pressure
H	Height (meter, m)
ω	angular velocity, $\frac{2\pi}{T}$; frequency, $f = \frac{1}{T}$, Hz
η_T, η_D, η_G, η_{PCOND}, and $\eta_{PTAKE-OFF}$	Efficiencies: turbine, drive train, generator, power conditioning and power take-off
C_P	Power coefficient
v	Water or fluid velocity (m/s)
U	Horizontal flow velocity in the x-direction (m/s)
V	Horizontal flow velocity in the y-direction (m/s)
W	Vertical velocity in z-direction (m/s)
ω	Sigma coordinate vertical velocity (m/s)
G	Acceleration gravity (m/s^2)
$(2\Omega\, X\, \vec{V})$	Coriolis force $(fz \times \vec{V})$
Ω	Rotation rate of the earth, 72.921159 micro radians/second
$\mathcal{F}_r$	x, y and z components of friction

T_S	Periodic time (seconds)
V_R	Flow velocity at the rotor (ms^{-1})
P_E	Electric output power of device (W)
P_H	Hydraulic power across capture area of the device (W)
P_I	Installed power of the device (W)
P_R	Hydraulic power at the rotor or turbine (W)
P_S	Turbine shaft power (W)
e_H	Hydraulic efficiency of the ducting
e_E	Electrical efficiency
e_R	Rotor or Turbine efficiency
$-\frac{\nabla P}{\rho}$	Pressure gradient force: $-\frac{\nabla P}{\rho} = -gz - \Omega \times \Omega \times \mathrm{r}$ gravity force, $-gz$; centrifugal vector, $\Omega \times \Omega \times \mathrm{r}$; angular vector, Ω;
$\vec{V}$	Velocity (u, v, and w) in direction (x, y, and z)

Table 1-1 KEY LAWS ON TIDAL SCIENCE [30]

Johannes Kepler, 1571-1630	Laws of planetary motion and the 'sphere of influence of the moon's attraction to the earth' which later invoked the force, Newton referred to as 'Gravity.' Orbit of a planet about the sun is an ellipse with the sun's centre of mass at one focus which is given by: $\frac{x^2}{a_K^2} + \frac{y^2}{b_K^2} = 1$, where x and y are the Cartesian coordinates, a_K and b_K are the lengths of semi-minor and semi-major axes respectively.
Galileo Galilei, 1564-1642	Earth's dual motion, around its axis and annual rotation around the sun had similar effect around the sun on oceans and other bodies.
Isaac Newton, 1643-1727	Newton's Laws state that: Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it. The relationship between an object's mass (M), its acceleration (a), and the applied force (F), is F = Ma For every action, there is an equal and opposite reaction.
Renee Descartes, 1596-1650	The laws confirmed Kepler's on the gravitational effect of the moon's attraction of ocean waters and other bodies and Galileo's heliocentric solar system, but nullified Galileo's concept on daily rotation of the earth about its own axis only.

LIST OF ABBREVIATIONS

Vision 2030 - The Kenya Vision 2030 is the national long-term development policy that aims to transform Kenya into a newly industrializing, middle-income country providing a high quality of life to all its citizens by 2030 in a clean and secure environment. The Vision comprises of three key pillars: Economic; Social; and Political.

GHG - Greenhouse gas emissions

Energy strategy roadmap 2050 - European Commission in 2011 set a long term goal of reducing GHG emissions by 80-95% when compared to 1990 levels, by 2050

IEA - International Energy Agency

NOAA – National Oceanic and Atmospheric Administration

UHSLC – University of Hawaii Sea Level Centre

OTEC - Ocean thermal energy conversion

NPP - Nuclear power plant

KNEB - Kenya Nuclear Electricity Board

PRO - Pressure retarded osmosis, and

RED - Reversed eletro-dialysis,

ERC – Energy regulatory commission

WIO – Western Indian Ocean

IPP – Independent power producer

TST – Tidal stream turbines

TCS – Tidal current speed

WIOEO – Western Indian Ocean Environment outlook

NREL – National Renewable Energy Laboratory

UNEP – United Nations Environment Program

REA - Rural Electrification Administration

IED – Innovation Energy Development

FSWG – Fixed speed wind generator

UPQC – Unified power quality conditioner

KMFRI - Kenya Marine Fisheries Research Institute,

LIST OF DEFINITIONS

A fluid is matter in a readily distortable form, so that the smallest unbalanced external force on it causes an infinite change of shape, if applied for a long enough time.

Reynolds number, Re is a dimensionless number (ratio) in fluid dynamics which help predict the change in flow type (Laminar or Turbulent):

$$\mathrm{Re} = \frac{\rho v L}{\mu} = \frac{vL}{\nu} = \frac{\text{inertial forces}}{\text{viscous forces}}$$

A water wave, as observed in the ocean is the outward manifestation of the transmission of a series of disturbances caused by winds, earthquakes, volcanoes, and landslides.

POWER QUALITY AND CONTROL

Increased demand on reliabilty and stability due to variablity in regulation and assymmety.

Tidal assymmetry is environmental distortion to the duration inequality of flood and ebb.

INSTALLATION WORKS

Defined in relation to time, space, and cost requirement

Operation, security and maintenance cost - benefit analysis requirement is based on national and global interaction among the coastal communities.

TURBINE PROCESSES

Angle of attack is the angle the object makes with the direction of the waterflow measured against a reference line in the object signified by $\boldsymbol{\alpha}$

Chord line is the reference line from which measurements are made.

Drag force is the force exerted on an object by fluid flow acting in the direction of fluid flow.

Lift force is the force exerted on an object by fluid flow acting in the direction perpendicular to the fluid flow.

Tip speed ratio T_{SR} is the ratio of the blade tip velocity to the fluid velocity.

Torque, T(N) is force exerted tangentially on the shaft by the rotor blades, T = Fr (F, fluid force, r, distance of the point of action from the axis of rotation, r).

Shaft Power, $PS\ (W) \ = \frac{2N\pi T}{T_S}$

Effective blade number, N'is the number of blades fully impacted by the flow at any one time. The shaft power can be determined from knowledge of the dimensions and rotational speed of the rotor(or tip speed ratio) and the force on the blades.

CHAPTER 1: INTRODUCTION

1.1. Assessment of tidal energy resource for production of electricity

With the evolution of marine tidal resource energy in parallel with improvement on the quality and quantity of data management in validated numerical simulations, it is appropriate to re-assess the potential of a region and its significance to the community. The coastal environment in relation to flow and mixing processes was instrumental to quantify marine tides and tidal current energy resource potential along Mombasa and Lamu coastal regions in Kenya [1]. The flow and turbulence data characteristics computed from the difference between upstream and downstream hydrodynamic concentration were crucial in the design of numerical models to simulate tidal current transport properties [2]. The database quantities used to establish whether tidal energy extraction was attainable and sustainable as an alternative source were the velocity profile, frictional force on the flow, turbulence intensity and varied coefficients which described the mixing of momentum and scalars [3]. The waves and tidal oscillation parameters undergo complex variations in space and time on account of strength of generating forces and proximity to angular velocity of the earth's rotation. Comparison of electrical energy sites for tides and tidal stream generation was significant to account for circulation dynamics such as sea-level and bathymetry's influence on deployment of the device [4]. The ocean tidal stream power estimate focussed on power density, converter performance, energy recovery, process economy and their optimization through cost-effective production processes with minimum environmental effects. Numerical modelling of ocean dynamics requirements was substantial to validate coastal flow measurement parameters, for instance turbulence intensity features in narrow channels and shallows possess higher tidal current energy with greater influence to an industrial commercial market [5], [6], [7], [19].

Tides are local stream pulses generated by astronomical forces caused on the earth's oceans, seas and bays by the gravitational attraction of the moon and to a lesser extent the sun. Tidal currents occur with the same alternate rise and fall of tide. The tidal currents that ebb and flood in opposite directions are called "rectilinear" or "reversing" currents [8]. Tidal energy is replenished by solar energy, wind, gravity, salinity variation, Coriolis forces, and earthquakes. Kenyan coastal environment with a narrow continental shelf characterized by the warm East Africa coastal and the cooler Somali currents, close proximity to the Equator with Tana and Athi rivers drainage into the Indian Ocean and physical features were investigated for sustainable energy development, but keen on marine reserve protection.

For developers, the examined tidal resource power estimates and tools established: (i) the tidal dynamics data for commercial scale turbine farms, (ii) prediction of sites optimal for locations of the tidal plant installation and (iii) the maximum available energy applying both theoretical analysis and hydrodynamic modelling. The process explored the determination of an optimal number of turbines, and the corresponding maximum electric power production [9] - [11].

For ocean resource users, the impact of energy extraction on the physical environmental changes or disturbances contributed by tidal current relative to a state of uniform rotation was a subject of investigation on the extent the marine livelihood can be affected or preserved. Technology barriers, converter system development and optimization were analysed with minimal focus on array configurations, installation, grid integration, operation and maintenance with regard to regulatory and legal affairs [12].

1.2. Site Details

Kilindini channel illustrated in Figure 1.1 is the link connection between Mombasa Island and the open Indian Ocean with substantial estuarine circulation due to drainage patterns from the Tudor Creek and Makupa Causeway, whose tidal ranges are in excess of 2 meters. Mombasa, being one of the Kenyan counties with an estimated population of over 1.2 million in 2016 is strategically located to host two extensive ports along the rich Western Indian Ocean reserves.

Figure 1.1 Site Details for Mombasa 4˚ 2' 13" S and 39˚ 40'11" E

The merits derived from the Kilindini port implied a potential development area with a rich mangrove ecosystem leading to a thriving tourist industry. The circulation patterns considered were determined by topography, atmospheric pressure, freshwater inflow resulting in the density structure and stratification with a progressive salinity gradient. These were further modified by artificial dredging, improved navigation and docking facilities provided to accommodate larger marine vessels. Kilindini contaminant transport and storage were crucial features which projected on settlement for the choice of site. Tidal energy is a sustainable investment of ocean resources for economic growth and improved livelihoods with low emissions, resource-efficient endorsing huge capital returns, [13].

Kenya's coastline commonly known as, 'Ten-Mile Strip' is 1420 km. Lamu is 650 km long as shown in Figure 1.2, which represents 45.7 percent of the total stretch in addition to an irregular coastline with several islands within its boundaries that have inadequate supply of electrical energy, [14]. Massive tidal flows in the seas are in one way driven by the combined gravitational pull of the sun and moon, according to Sir Isaac Newton described in Table 1-1. Secondly, the complex coastal shapes and bathymetric variations are instrumental in rejuvenation of these tidal flows into a dynamic resource which can be harvested to generate renewable electricity, [15].

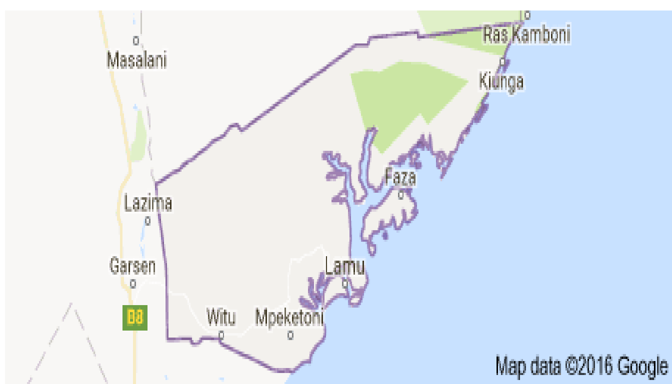


Figure 1.2 Site Details for Lamu, 2˚ 16'11" S and 40˚ 54' 2" E

1.3. Problem statement in renewable and non-renewable energy industries in comparison to promoting development of marine tidal resource energy

The main limitations on over-dependence of traditional fossil fuels (oil, gas and coal) as energy sources are imminent scarcity, vulnerable cost, emission of greenhouse gases (GHG) and environmental issues due to climate change. This has increased diverse renewable energy technologies depending on the resilience of the energy supply system relative to competition, growth and economic development. The fossil fuels producing countries geographical location, inconsistent fuel costs, distribution and unexplored reserves, have led to political instability mainly in the Middle East [16]. Also, fossil fuels and nuclear power stations experience critical challenge of reaching their useable life, culminating to rising fuel costs and infrastructure security [17].

Coal-fired generation supplies accounted for 41% of electricity globally in 2006 [18]. The Coal-fired generation capacity is yet to realize enormous expansion particularly in countries with rich resources including Kenya. Coal-fired generation energy was projected to double from 7400 TWh in 2006 to 9500 TWh in 2015 and 13,600 TWh in 2030 [19]. Replacement of the Coal-fired generation plants with tidal stream power plants could reduce GHG by 10 Pg $C0_2$-eq/year (~10^{10} tonnes/year). This would realize a 40% reduction of global GHG emissions [20] - [22].

Renewable energy is “clean”, obtained from natural and persistent flows of energy occurring in the immediate environment which include nuclear, solar, ocean, geothermal, photovoltaic, hydro, wind, biomass fuels, and biofuels [23]. Evidence of incredible growth and deployment of diverse renewable energy due to an increased emphasis on environmental protection and government energy policy awareness is notably significant. The incentive focused on decarbonising electricity supply, improving energy efficiency, energy security and affordable future energy supply network with an emphasis on utilizing natural resources, [24] - [25].

A feasible energy source in the contemporary electric power industry must undergo adjustments due to the intermittent supply required to meet the inevitably constant, reliable and consistent demand. A utility provider should be dependable, predictable in production, accessible, and with measured quantity for comparison to other generation sources meeting the demand [26]. This constitutes a complication for renewable energy generation technologies that are dependent on atmospheric conditions, such as solar, wind and waves due to their stochastic variability. Tidal power depends on astronomical forces rather than atmospheric conditions, promising consistency compared to solar, wind or wave power [27] - [32].

Local tidal current variation effects on energy loads, fatigue, physical obstruction and erosion on the channel bed are crucial features for study on reduced performance. Analysis of the tidal current transportation data process at a particular location should be properly characterized for at least 29 days of continuous measurement, the variation being predicted with a considerable accuracy of over the entire 20- or 30-year life of a tidal power investment [33] - [35].

Significant assessment to quantify the tides and tidal currents resource potential along the Kenyan coastline as a source of renewable energy in regard to farm sizing and positioning was the hydrodynamic and hydraulic condition for efficient power extraction [36] – [38].

Testing and evaluation of marine energy potential was analysed to interpret, resource characterization and mapping, business enterprise plans for economic investment quest relative to extraction device (type, performance, and cost), and impact assessment (social, environmental and security) [39] – [40].

Oceans are a vast renewable energy resource, underutilized due to delayed ocean technology development in Africa, for example, inadequate skills and legislation. Offshore machinery installation is very costly, though the potential is a grand scale project with prospects to make major and diverse contributions to the generation of carbon free energy governed by astronomy, [41], [42]. Subject to seasonal variations, tidal energy is available 24 hours a day hence can be used as base load power. Installation and legal limitations, for example, long submarine cables or the exclusive economic zone restrictions are considered in relation to full scale implementation. Environmental risks e.g. corrosion and biofouling, which is the accumulation of algae, microorganisms, marine life on the pipes surfaces, are a concern on the infrastructure.

Tidal streams majorly characterised by sea currents at high velocity are a creation of the tides' periodic horizontal motion, frequently magnified by topography structures like inlets to inland lagoons, headlands, and straits. France, East Asia, Canada and Scotland, are examples of countries offering ideal tidal extraction conditions [43]. New United Kingdom plant with small arrays of 4 to 16 MW to be installed are evidence of global development momentum and marine energy industrial forecast by 2035 [44], [45].

The optimum configurations for tidal current conversion systems are with reference to viscosity, pressure, density, channel space, and flow velocities using Matlab/Simulink and excel software models. The observations showed that the integration of the software models reduced programming time and introduced a variety of new functionalities and characteristics of the flow simulation in relation to buoyancy, gravity, tether and dynamic physical oceanographic processes [46].

For ocean energy to become competitive with traditional sources of electric energy, the cost per kWh must be reduced, [47].

1.4. Current status of tidal energy generation for the East African countries

Western Indian Ocean WIO countries, Kenya, Tanzania, Mozambique and Madagascar exhibit insufficiencies in the electrical energy supply sector including infrastructure, high costs of thermal energy and technology challenges [48], [49],. Mainland WIO countries all endure up to 20% deficit in electrification levels at the national level and from 1 to 11% for rural areas due to transmission and distribution technology not fully developed, [50], [51]. But, access to the cost-efficient hydro-power is low and poor in coastal and island regions due to lack of data measurement schemes, personnel capacity and infrastructure. The urgent need is to intensify the use of diverse renewable energy sources in order to enhance rural electrification administration REA, systems security and sustainable supply [52]. Expertise on device performance on combinations of distinct renewable energy sources, evidenced by the turbulence, flow patterns and velocity distribution was fundamental towards sustainable energy development [53] - [55]. However, the current shortage of full spatial-temporal estimation of tidal stream energy resource for the WIO coastline down to the scale of individual devices, (regardless of grid connection, inter-device and inter-array interactions), is an obstruction to the complete implementation of tidal current energy technology [56], [57].

Velocity (v) varies parabolic-ally from zero at the base of channel to maximum at the surface, or vice versa. Velocity gradient, also known as turbulent diffusion varies directly proportional to shear stress, ranging from maximum at the base level to zero at the surface, and it determines the transport of heat, momentum, solute and suspended matter. Fluid momentum is created by the downstream pressure gradient and gravitational forces of gravity which are then transported on account of the boundary to the flow. There also exists resistance that depends on mean velocity and flow depth [58].

It was crucial to set up tools for measurement of the ocean waters' resource with reasonable accuracy for a holistic analysis to cope with different situation and scenarios to allow the user to extend or modify models according to the specific needs. The ocean energy resource assessment was able to apply excel and MATLAB/Simulink environments with enabling block wise modelling tools that provide simple, handy and flexible software to establish individual extraction processes and their interactions in a relatively simplified modeling framework [59].

Traditional ocean observation through monitoring of gauges and stations are slowly being upgraded to usage of model tools towards prediction of tides and their flow characteristics. The real-time data facilitate data coverage for bathymetry and the coastline region, unlike the model which may undergo rigorous calibration of parameters to account for variations in size and type of roughness present in the coastline. On the other hand, these site specific topographical features such as inlets and headlands, influence flow hydrodynamics. To address the limitations and challenges scientists and engineers complement on-site field measurement coupled with numerical simulations [60].

1.5. Aim

The scope was to quantify the tidal energy potential for electric power production, identify economic constraints and recommend on suitability to a resource characteristic. The thesis question addressed whether tidal stream plants are a feasible option for the Kenyan coastline and if so, which is the viable conversion scheme. The tidal current speed (TCS) predicted power generation impacts on tidal stream energy conversion, hydrodynamics characteristics and flow regime in a tidal groove or estuary passage near a coastal headland [61]. Choice of tidal power generators and conversion devices involved design, size, capacity and site (water depth) aspects in a bid to capture the massive kinetic motion in the ebbing and surging of the ocean tides. The analyzed marine hydrodynamic data profile from which calculations and simulation of tidal power technologies, device performance, site variations in the tidal resource, future prediction estimates were evaluated. It was vital to establish proper design loads at a particular location for enhanced prospects of predictable resource characterization, mapping, and sensitivity in the integration modeling of grid resolution of renewable energy resources [62].

1.6. Objectives

1.6.1. General objectives

To estimate the resource potential of marine tides and tidal stream energy for reliable extraction of electrical renewable energy sources along the Kenyan coastline.

1.6.2. Specific objectives

i) To design hydrodynamic analysis models for simulation of a marine energy converter.
ii) To assess the model performance
iii) To predict a cost-benefit analysis to evaluate marine tides and tidal stream energy generation

1.7. Justification for the Study

A considerable amount of sea level data is archived in different data centres within and outside the Western Indian Ocean region. In spite of the professional capacity available, limited use of data has been made for scientific and practical applications, [4], [38].

Area dimensions, site location of land masses, as well as shape and depth configuration of the ocean floors greatly influence productive tides characteristics. Comparison of data estimate from the modelling system on the tidal stream resource, with the experimental channel flow characteristics whose tidal current data is provided by National Oceanic and Atmospheric Administration, NOAA, ascertain the model's operation and resolved accuracy. The model execution was then applied to calculate the distributions of current and power density over a spring-neap cycle and also estimate the tidal stream energy resources around

Lamu and Mombasa [63].

1.7.1 Advantages of marine tidal stream energy design

The superior sea water density equivalent to 800 times that of wind, crowns ocean tidal energy the capacity to offer an effective and reliable source of electrical power which curbs environmental threat with minimum waste and noise pollution produced [9]. For the same surface area, water moving 12 knots exert the same amount of force as a constant 110 knots wind, hence tidal currents contain an enormous amount of energy that can be captured and converted to a usable form [3], [64].

Compared to the barrage type [24], the current tidal stream conversion device, namely the second generation and technology advancement, least affect wildlife/marine life, channel silt deposits and size/weight leading to reduced building, operation and maintenance costs [65].

The increased energy security by exploiting indigenous resources e.g. tidal energy promotes decarbonisation of electrical supply and minimum dangers of radioactive fallout, reduced operating costs for example, transport costs due to resident energy utilization and maintenance of generating facilities with minimal fuel cost.

Predictable and less intermittent source of electrical energy compared to irregular wind and solar energy enhances scheduling and advance planning. Energy mix explores competition, contributes to diversity, reliability and curb effects of fuel reserves' depletion. Flood control and sea obstruction, aquaculture farming and economic growth of remote coastal regions would improve infrastructure, recreational facilities and development of secondary industry. The International Energy Agency estimates the global output potential of tidal power plants to be as high as 800 terawatt-hours per year, enough to supply 250 million households with electricity [26], [44]. Renewable energy resources replenish themselves and can be used over again and again [24], [40].

1.7.2 Disadvantages of ocean tidal power

Despite negligible fuel cost for ocean renewable resource equivalent to zero, the capital cost can be notably large in amount; however, government subsidies exist to help. For renewable energy investment to thrive it must become cost competitive and consistent with non-renewable sources [9], [13], [30], [38]. Presently the greatest challenge is the high cost to build and maintain; a 1085MW facility would cost as much as 1.2 billion dollars to construct and run [66].

Technology is not fully developed hence factors including grid connection, suitable site with reliable, strong and consistent currents features able to withstand rough weather are vital yet critical, taking into consideration possible security threat to navigation infrastructure and collisions with energy conversion devices. Ocean energy sources with unstable, intermittent and controllability characteristic brings a number of challenges to the integration of micro-grid and traditional electric power grid [67].

Barrage type of extraction generates energy for about 10 hours out of the full-day and has environmental effects, for example, fish and plant migration, silt and sedimentation deposits, and local tides change (effects still under survey) [68], [69].

1.7.3 Environmental concerns

Tidal flows are typically turbulent and must be modelled taking into account interactions of sedimentation patterns effect, e.g. turbidity, total suspended solids and water viscosity, all which have an impact on ocean water quality, marine life, irregular topography, transport constrictions, and thus complicates the flow [37], [45].

Adherence to pre- and post- observatory, construction survey information, policy recommendations on regulatory jurisdiction over the project scientific requirements, such as the challenge to include the effects of high Reynolds number, and rough topography used to study different properties of tidal flow [70], [71].

Developments encompass large embayment which affects wide geographic areas, thus possible variations of primary and secondary productivity structures in coastal waters, fish mortality, and sea level fluctuations, leading to local and regional socio-economic impacts [37], [72].

1.8 Scope of work

The research subject and schedule focused on two ports, Kilindini and Lamu. During an attachment at Kenya Marine Fisheries Research Institute, KMFRI Mombasa from 9th July to 7th October 2016, [APPENDIX D], one array was deployed at Kilindini weather station at a mean depth of 50 m to measure marine tidal currents resource and their characteristics for "site assessment-pre-feasibility" study.

No specific Technical Energy Conversion System, TECS characteristics were considered so the horizontal axis turbine was employed to compute the amount of energy to be extracted being the most dominating wind and tidal stream technology adequate for electrical production.

The bulk of the data used in the thesis were analysed from bathymetric charts developed by the University of Hawaii Sea Level Centre (UHSLC), from installed SLPR2 at Kilindini weather station. It collects and transmits data via Global Positioning System, GPS. These data and technical products have been complemented with General Bathymetric Chart of the Oceans, Gebco (5th edition) database in order to obtain a more detailed bathymetry of the Mombasa and Lamu Ports. The Kilindini channel is a large natural deep-water channel, characterized by a complex system of constrictions and sills [10], [23], [30], [31]. The bathymetry progressively narrows entering into the port, from near 1000 m in the Mama Ngina drive area (the sub-basin adjacent to Likoni side), to about 500-600 m in the northern Port Reitz. West of this section it further gets narrower in the so called Mtongwe Narrow (MN) characterized by a bathymetry of more than 800 m until reaching the minimum width section. Further west, the bottom abruptly slopes reaching the minimum depth of the whole canal, (290 m) and Strait. More to the west, the presence of a submarine ridge called Tudor Creek divides the outflowing cross-section into two channels [30], [32]. The northern channel has a maximum depth of 250 m; just south of the bank, the southern channel a depth of 360 m in the topographic point called Espartel Sill (ES), [10], [23].

The past projects steered growing concern on the Kenyan marine energy industry development especially on generic modelling of tides and tidal resource stream exploitation.

Economic projections were essential for commercial tidal research incubation, development, installation, testing and protection.

Evaluation and utilization of tidal stream energy resource emphasised on the global trends in energy efficiency on tidal resource model resolution and mapping. The marine energy efficiency was analysed with respect to constraints and challenges in relation to fluid transport, conversion devices, cost, evaluation, collaboration and consultancy evaluation schemes.

The thesis report was presented in five chapters: Chapter 1 describing fundamental theoretical analysis on pre-feasibility design, experiments and measurements made to analyse the Kenyan Indian Ocean resource. This entailed data analysis, numerical modelling of physical oceanography equations, computation of hydrodynamic conversion to rotary motion, and finally to electrical conversion schemes. In chapter 2, the global marine energy resources, technology and challenges were compared to Kenyan infrastructure with an intension to establish the extent to which capital investment on exploitation has been or is expected to be realized locally. Chapter 3 was a software interpretation of the Ocean energy mechanism, modelling process incorporated after the calibration and verification of the build-up model in accordance to the database collected. In summary, the literature review, compilation of database, survey (interviews seminars and conferences) and modelling tools developed a framework for resource and technology assessment with defined rules to match a particular characteristic, [23], [33].
Matlab and Excel implemented the Mombasa and Lamu data and proved robustness of work to further qualify mathematical characterization of the resource and technology reliability. Chapter 4 and 5 were a summary of simulation analysis results, conclusions and recommendations.

1.9 Summary of the main thesis focus, [14], [22]

Theoretical estimate behind tidal stream power distribution and potential were as follows:

1.9.1 Resource feasibility and layered mapping

More hydrological data should be collected over longer period of time which requires a network of gauging stations along with human capacity building. The selection of tidal stream energy converter farm locations was made upon assessment of:

i) Tidal current velocity and flow rate in consideration to the direction, speed and volume of water passing through the site in space and time.

ii) Site characteristics assessment including bathymetry, water depth, geology of the seabed and environmental impacts to determine the deployment method and the cost of installation.

iii) Electrical grid connection and local cost of electricity to account for the seafloor cable distance from the proposed site to a grid access point and the cost of competing sources of electricity to determine the viability of an installation.

1.9.2 Environmental conditions

Site assessment considered the constantly changing hydrological and environmental conditions affecting the Western Indian Ocean. Environmental regulations, policies and tariffs were investigated to increase deployment of renewable energy to expand energy access, particularly in rural off-grid areas. Focus on climate change and development to increase electricity and clean energy.

1.9.3 Technological improvements

Technical equipment, innovation, design and development framework for tidal energy resource and technology evaluation needed to be identified to establish the infrastructure.

1.9.4 Planning, finance and implementation

Implementation regulations had to avoid conflict between electricity, fishery, agriculture and biodiversity. High costs should be overcome with improved access to finance for research and project development. Awareness should be raised in order to improve the risk assessment and to provide conducive loan conditions. Electricity network planning would help identify improved investment into the grid infrastructure Administrative procedures need to be simplified to improve collaboration among water resources agencies, electricity, environment and authorization processes. Coordination, collaboration and knowledge exchange for professionals, industry and stakeholders need to be expanded to promote local and international dialogue.

1.9.5 Analysis of the results and conclusion

Site characterization of tidal flow energy, marine life presence, water quality, seabed geology and biofouling potential were operationally meaningful variations to resolve the power density and direction.

1.9.6 Thesis report defence

The choice for location of a tidal stream power converter farm depends on available tidal power, site features, (bathymetry, water depth, flow patterns), economic and social impacts of the project.

CHAPTER 2: LITERATURE REVIEW

2.1 General aspects of energy generation

Energy constitutes the motive force of civilization and it determines to a high degree, the level of economic and social development of a given country. International Energy Agency IEA, in 1974 launched FOUR global coordination indicator targets on (i) energy security through promotion of diverse electricity sources that are efficient, flexible, and reliable, (ii) economic energy development for trade balance, to foster growth and eradicate poverty (iii) set regulatory environmental standards to counteract energy impact and greenhouse gas emission (iv) global collaboration and partnership to solve energy and environmental concerns.

In general the costs per unit of generated energy, and optimum transmission, distribution scheme, increases towards relative competitiveness on energy intensive industries, and consequently towards decarbonisation as presented in the low carbon economy roadmap 2050 [75] - [77]. These are essential considerations in regard to socio-economic development and the government has the mandate to ensure secure and sustainable supply of energy to their nation [78].

A diverse portfolio of energy solutions is thus needed to meet the future energy challenges through modernization of generation, transmission, distribution and energy use systems. The development and implementation of the efficiency energy technologies should both minimize energy waste and improve energy conversion management efficiency. This implementation requires strong leadership and dedicated international cooperation amongst stakeholders.

Kenya's current energy generation forms are as follows:-

(i) Fossil fuels - (crude oil, liquid oils, gas, and coal) stands at 525 MW. These are non-renewable methods of producing thermal energy. The uneven distribution of the fast growing exploitable indigenous non-renewable energy production also provide diversity, but their inherent centralisation expose them to extensive inadequacies e.g. expensive cost of generation, whereas the renewable energy resources tend to be spread in nature, enhancing their security field [79]. The renewables methods of producing energy, which have already realized a modicum level of commercialization, are hydro-electric power, geothermal, solar and wind.

(ii) Hydro-electric power generates 766 MW, is safe and can be regulated by controlling the volume of water, though it suffers environmental consequences through damming and the capital investment is expensive. The erratic rainfall patterns in Kenya, further contributes to low levels of water flow, a negative impact on hydropower production.

(iii) Geothermal resources in the Great Rift Valley (Olkaria I and II) generate 200 MW. Geothermal fuels unfortunately cannot be transported to far distances like fossil fuels hence are directly utilized on or close to the resource. The limiting factors here are policies and legislative framework which are unattractive to private developer's exploration, growth and development of the resource to be realized. The main advantage is minimum waste disposal as energy is extracted from the water enthalpy at 140˚C and then injected back to the earth crust at 40˚C after use.

(iv) Solar power installation has grown tremendously at a daily insolation of 4-6 KWh/m^2 following the World Bank and International Finance Corporation, IFC partnership under Lighting Africa initiative [80]. Kenya government has zero-rated import duty, removed value added tax and also provided the policy and energy framework as per the Energy regulatory commission, ERC.

(v) Wind energy currently generates 5.75 MW. It replenishes itself with the technology advancement towards economic, social and environmental benefits. Investment of wind electric power technology not only meet energy needs but also reduce greenhouse gas emissions and support green growth by accelerating deployment and cross border trade through a continuous renewable power network that runs from South Africa to Egypt. Wind driven waves can be categorised as incident containing large amounts of concentrated energy potential and the vast offshore wind energy enormous along the nation's coastline.

(vi) Nuclear energy according to Kenya Nuclear Electricity Board (KNEB) is in the development stage, based on site selection; development of national strategies for radio-active waste management; emergency preparedness; nuclear fuel cycle; and nuclear power plant (NPP), feasibility study. This has realized positive progression due to government support for the programme [81].

Kenya adopted Feed-in-Tariff (FIT), 2008 policy has expanded renewable generated energy sources by promoting Off-taker discount rates which facilitate pre-determined tariffs for a given period of time. The FIT and Rural Electrification Authority, REA are government's effort targeting increased access and the use of renewable energy. This has initiated discussions on current challenges which include financing and expansion of renewable energy incentives, for example the Strathmore Solar project [82].

2.2 Marine Renewable Energy resources

Oceans waters cover 70% of the earth's surface, a vast source of energy which constitutes potential renewable energy resource that could be harnessed to supply more electricity production [83]. Numerous techniques for extracting marine renewables can be sub-divided into the following generating technologies: chemical, biological products, thermal, and mechanical.

Ocean energy renewable resources are waves; salinity gradient; oceanic bioconversion; ocean thermal energy conversion OTEC; tides and tidal current energy. Though they possess greater reservoir of power, and technical feasibility as other renewables, they have not witnessed commercialization in Kenya. Renewable energy sources RES, in the Western Indian Ocean comprise of the least investigated generation conversion potential having only been examined in theoretical research analysis and not practical

(i) Chemical Generating Technology

Salinity gradient, is a chemical form of generation, energy is extracted from salt concentration difference between two fluids commonly fresh water and salt water as summarized in Table 2-1, where a river flows into the sea. Conductivity value in Siemens per centimetre, S/cm is the measure an aqueous solution conducts electrical current. Specific conductance is a conductivity measure in S/cm made or corrected at 25°C. Total dissolved solids, TDS is an estimate of the mass dissolved solids in grams per litre, g/L or parts per million, ppm derived from conductivity reading using a conversion factor e.g. sodium chloride has a TDS factor of 0.49 and sodium bicarbonate has a TDS factor of 0.91. Salinity is similar to TDS, that is, an estimate of the level of salt in a water sample from the conductivity value using a conversion factor of 0.5 g/Kg or parts per thousand ppt. Salinity values are reported based on the dimension less practical salinity scale denoted by psu [84].

Table 2-1 Salinity levels

Water quality	**Pure water**	**Tap water**	**Sea water**
Conductivity S/cm	0.055 $\mu S/cm$	$50 - 100$ $\mu S/cm$	53 mS/cm
TDS, g/L or ppm	500 ppm	2	2.2-3.6
Salinity, g/Kg or ppt	35	0.5	30-37 psu

There are two salinity gradient techniques:

i) Pressure Retarded Osmosis (PRO), and

ii) Reversed Eletro-Dialysis (RED)

PRO uses a membrane which separates salt concentrate from freshwater. This creates pressure in the sea water chamber turning the turbine arrays to compensate the pressure hence generate power. RED cultivates energy from the salt ions transport through membranes. It employs a stack of alternating anode and cathode exchanging perm-selective membranes moving ions to anode and cathode depending on their charge. In RED torque is produced by the electrolytic ion exchange creating a potential difference for energy to flow [85].

Conductivity of water bodies is dependent on the specific ionic composition present, circulation, density, and temperature changes [45]. Salinity values outside of a normal range can result to marine life death due to changes in dissolved oxygen concentrations, osmosis regulation and TDS toxicity.

The major challenges are (i) the chemical and biological feed-water activity on the converters, and (ii) the high price of the membranes. The thermodynamic analysis with proximity to the equator solar energy at four times higher than at the poles, yield 2.3 MJ per m^3 of sea water (2.6 TW). The potential is enormous estimated at 20% of the current global electricity demand. Energy can be extracted from natural or industrial salt brines. [86].

Kenyan sites are divided into six salinity categories as shown in Table 2-2 (SAL1–SAL6); sites two and three as well as sites four and five are combined since they are equal, [20], [21].

Table 2-2 Characteristics of the range of expected salinity gradients sampling sites in Gazi

Site*	*n*	Tw number†	Age (years)‡	Salinity (‰)§	Salinity category¶	Inundation class**
1	10	55904 to –08, 56705 to –09	9–16	26·4	1	3
2	5	56710 to –14	17–37	31·9	2	3
3	4	55883 to –86	11–22	33·6	2	1
4	5	55872, –73, –76, –80, –81	17–33	35·2	3	2
5	5	55958, –75, –78, –90, –91	4–5	35·4	3	3
6	10	55890 to –94, 56725 to –29	11–24	38·2	4	2
7	7	55887 to –89, 56730, –33, –34, –36	25–57	42·7	5	4
8	4	56721 to –24	4–20	49·2	6	2

*****Gazi site, † accession number of the samples in the Tervuren wood collection ‡ Cambial Age in 1998, **§** soil water salinity at 10 cm depth, ¶ salinity categories Inundation class according to Watson 1928 in Macnae 1968 [87].

(ii) Thermal Generating Technology

The sun's heat results in a temperature difference between the surface and deep waters of the ocean.

OTEC, a thermal form of power converts the extremely large temperature difference and extracts energy by utilizing heat engine. OTEC plants may be land based, floating or grazing [88].

(iii) Biological Products Generating Technology

Biomass in the ocean yields economical products including the renewable fuels for electrical production perceived as a carbon-neutral source of energy unlike net carbon-emitting fossil fuels of which copious use has led to global warming and ocean acidification [89].

Only a fraction of available ocean energy resources are conveniently located in sites which are economically viable for exploration with the appropriate science and technology invention. Nevertheless, this limited capacity of ocean energy progression could still make a substantial contribution to renewable form of electrical power supply. This explains why marine renewable energy scheme is currently at the center of interest in academic, industrial and research development around the globe [90].

Prior to implementation the hydrodynamic conditions must be investigated to facilitate the resource potential, choice of site and environmental impact [33], [91].

(iv) Mechanical Generating Technology

The two broad types of mechanical ocean energy are kinetic and potential.

Tidal barrage generation employs the gravitational potential energy extracted from the ocean tidal range by erecting walls, dams, sluice gates or tidal locks creating an enclosed tidal reservoir similar to a hydroelectric impoundment reservoir. Tidal turbine generators fixed in discharge tunnels spin as the ocean water rushes past them to fill or empty the reservoir thereby generating electricity.

The three main tidal energy barrage schemes are:

- Flood generation generates as the water enters the tidal reservoir
- Ebb generation tidal power is generated as the water leaves the reservoir
- Two-way generation tidal power is generated as the water flows in both ebb and flood directions.

Harvesting ocean wave energy

Waves are formed by the transfer of energy from the atmospheric motion (wind) to the surface of the ocean. Kinetic energy harnessed in the marine waves present varied industrial challenges on technology, for example unpredictable fluctuations hence a significant range of design models are currently being trailed for the most efficient technology [92].

Wave energy is proportional to both its oscillatory period and the square of its amplitude, which makes depths between 40 and 100m to be the optimal locations because their periods and amplitudes are both high. In shallow depths, the energy is dissipated as it interacts with the seabed while in deeper waters it's impractical and uneconomical to deploy a wave power plant. Wave energy concentration at low frequencies and low velocities makes efficient conversion and transmission to a grid difficult and limits the options for efficient power take off technology.

The FOUR wave conditions that influenced tidal stream resource were (i) waves aligned at an oblique angle to the tidal current; (ii) the angle must be considered in oceanographic analysis; (iii) waves exert significant impact on tidal stream resource; and (iv) reduction of the tidal resource by 10% per meter increase in wave height [93].

Tides and Tidal current renewable energy resources along the East African coastline are enormous as shown in Figure 2.1, compared to the stochastic nature of harnessing electricity from wind, solar and other currently unexplored marine energy resources [4], [30]. Tidal resources are notable in extent worldwide; unfortunately the varied conversion device technologies in relation to site geometric parameters are largely unmapped. The estimates of global potential of tidal energy resources vary, but it is widely agreed the capacity exceed 3 TW globally [94].

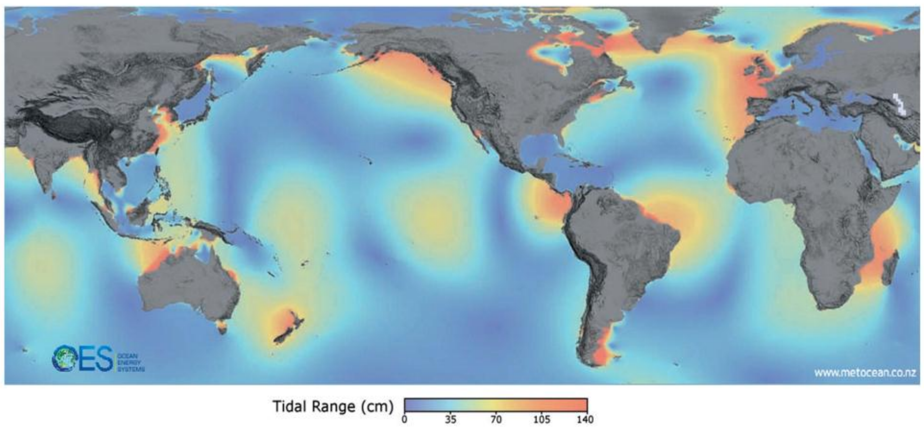


Figure 2.1 Global distribution of tidal range, OES, 2011

The principal drivers for tidal currents resource modelling for renewable energy range from its density, 800 times heavier than air, to the astronomical stature of the resource which depends on the extracting mechanism. The power yield essentially is a predictable ocean reserve, although subject to massive fluctuations forced by global climate patterns contributed by greenhouse gas emissions [15]. The analysis of tidal stream prediction and maturity, though deferred in a number of sites due to high initial investment costs is paramount for the successful integration of renewable resources into the electrical grid [8], [95]. Semidiurnal tide is dominant in Kenya whereby the largest marine currents occur at new moon and full moon (spring tides), and the lowest at first and third quarter of the moon (neap tides), [48].

2.3 Potential to harness tidal current as a source of electrical power

Marine tidal energy was one of the ancient types of energy sources that are not depleted which were employed by mortal man, as early as the eighth century [5]. This research is specifically focussed on evaluating the current state of energy extraction from tides for electrical power generation in Kenya, [31].

Locations with favourable waves, higher tides and tidal currents near the African coastline, Kenya included are shown in Figure 2.2 with an exceptional range beyond 4 metres.

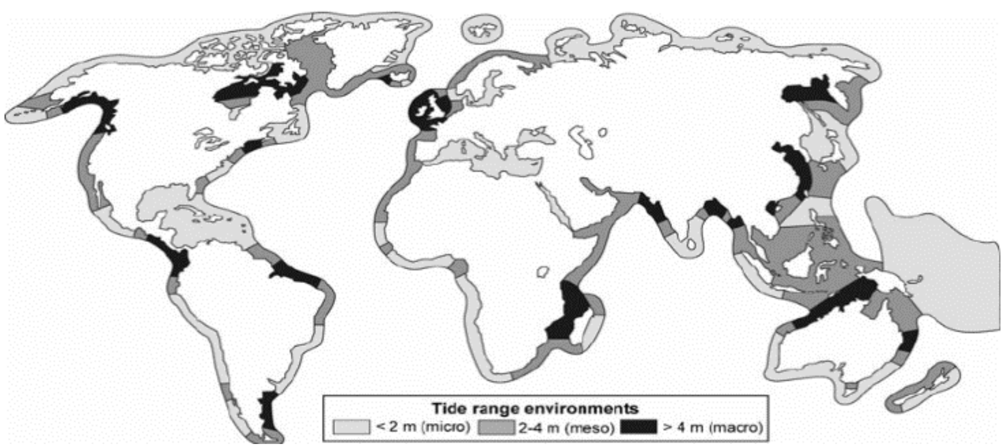


Figure 2.2 Global tides patterns by Davies 1980, modified by Masselink and Hughes 2003

Economics, environmental impacts, land-based conflicts such as ownership, land utilization, planning authority, noise contamination, grid interconnection and global surface effects impose further limitations on the resource available for energy extraction. Construction, technology and professional assessment employed in a marine energy environment currently exhibit immature pilot project processes with cost-competitive economic projections over the long term, though legislation and policies ensure environmental protection and promote sustainable strategic development, [23]. The infrastructure design should be capable of surviving more extreme weather conditions than those prevailing on shore, bearing in mind that the technology must never destroy the natural marine surroundings which are already under subjected distress from contamination, excessive overfishing, habitat destruction, and climate change [96]. Installation of technical equipment far offshore expose the long submarine cables to corresponding transmission losses leading to economics constraints and ocean logistics puzzle. Choice of site location should consider that negligible variation of tidal dynamics into the ocean further away from the shore exhibit an almost constant power output with increase in distance [26]. The working performance, upkeep and sustenance of plant at sites far distance in relation to the shoreline variability and trends with restricted weather conditions, must be examined to make the project commercially viable, [27].

Research and development goals included energy resource and topography, conversion efficiency, reliability, cost reduction, marine life, navigation, equipment survival in salinity and pressure environments, grid interconnection and research fund sourcing.

2.4 Tidal energy generation methods

The electrical power generated from the ocean tides and tidal currents employ diverse and relatively conventional turbine technologies which exist, for example:

i) Tides and tidal stream generators driven by power turbines which employ kinetic energy of water [85], [97].

ii) Tidal barrage generation process employs potential energy or specialized dams [26].

iii) Dynamic tidal power exploits interaction between potential, and kinetic energy. Tidal phase differences lead to a significant water-level differential in shallow coastal seas [27]

iv) Tidal lagoon, ‘U’ shaped breakwater harbour type structure, built out from the coast has a bank of hydro turbines in it that captures the potential energy of tides [9], [15]. Water fills up and empties the man-made lagoon as the tides rise and fall, generating electricity on both the incoming and outgoing tides, four times a day, every day.

2.4.1 Tides and Tidal currents exploration and extraction

Tides are the periodic waves which result in cyclical rise and fall phenomenon of the ocean surface together with horizontal currents and its inlets. The interactive forces between the tides and the Moon were discovered by Aristotle, and the Earth-centered astronomy persisted until 17th Century when Isaac Newton derived the equilibrium theory that was further developed by Laplace and finally Kelvin applied harmonic analyses which he introduced the harmonic current equation.

These forces, namely wind, gravitational interaction of the sun, moon and other astronomical features acting on the ocean upon the rotating planet earth, e.g. changes in atmospheric pressure, earthquakes, natural forces and are thus predictable [98]. The vertical motion of the sea drives masses of water horizontally creating currents. Most common waves are created by wind generated by unequal distribution of heat on the earth's surface when the wind forces over water drives waves. The energy concentration and transfer of the initial solar power equivalent to $1kW/m^2$ is estimated to 70 kW/m average wave power of crest length distance. This average value increases to 170 kW/m of crest length from June to September and 1MW/m or more during storms. Diffuse energy is characterized by implementing wave power performance, aggressive during storms, with a wide range of variation in wave size, direction, length and period. The irregularity of wave energy with an oscillating low frequency source creates the need for a converter scheme of energy to 50 Hz before connection to the electric utility grid, [31].

Spring tides are the largest and coincide with the new and full moon when the combined moon and sun are aligned gravitationally. Neap tides are smaller depending on the moon waxing or waning and the sun's gravitational pull not being aligned. The spring-neap cycle approximately has a period equal to 14 days. The variation of the tides throughout the entire year depends on the 14-day spring-neap cycle, in combination with the 14-day diurnal inequality cycle [30], [31]. The principal (lunar) semi-diurnal (twice daily) constituents are described by M2 (moon, twice daily) and a period of 12.421h, and solar semi-diurnal S2 (sun, twice daily) with a period of 12.00 h, while the principal diurnal (once daily) constituents are described by K1 and O1 symbols. The effect of the elliptic path of the moon around the earth is simulated by the constituents larger lunar elliptic semidiurnal (N2) and smaller lunar elliptic semidiurnal (L2). The effect of the moon's declination is simulated by the luni-solar declination diurnal (K1) and principal lunar declination diurnal (O1) constituents. Further, (K1) together with the principal solar declination diurnal constituent (P1) simulates the effect of the sun's declination [32], [33].

The tides at any site are described and predicted by summation of the contributions from all sinusoidal constituents, assuming their amplitudes, phases and frequencies are known, [34], [35]. Symbolically the tide level is:

$$z\,(t) = z_0 + \sum_{i=1}^{M} (A_1 \cos \omega_i \; t - \phi_i\,) \quad (1\text{-}1)$$

$$where\!: z(t) = water\ level\ at\ time, t \quad z_0 = sea\ level\ reference$$

$$A_1 = amplitude$$

$$\phi_i = phase\ shift\ angle \quad i\ to\ M = instantaneous\ time\ values$$

In recent years, researchers and investors have shifted their focus towards technologies that extract energy from tidally driven coastal currents [37].

The requirement being to measure the potential for extracting electricity from different sites and the equivalent power output with respect to the flow rate. Excel and Matlab mathematical and statistical modelling of the tidal stream resource estimates exhibit the tidal energy characteristics for ease of the resource predictability [11], [19], [99]. Reliable assessment and forecast quantities of tidal power analysis in Mombasa and Lamu reduce uncertainties, and increase investor confidence. The estimation was crucial for achievement of a prospective integration of renewable energy resource into the electrical grid [5], [21], [28].

The data variation of marine tides and tidal currents quantities from measurements in a tidal channel with flow magnitudes were used to analyze the hydrodynamic loads extracted from mass flow of water against a rigid stuctural element or system, [9]. Tides and tidal current measurements predicted the power extracted from an array of technical energy conversion systems (TECS), to ensure the tidal resource available is not over-extracted and cannot be depleted, [10]. The ocean circulation pressures were functions of flow velocity, direction in relation to obstruction, obstruction‘s geometry, and surface roughness characteristics. It was possible to verify the minimum constant power supply to the electric grid from tidal farms in appropriate locations and in suitable quantity. The maximum power extracted depends on tidal stream, coast morphology and environmental aspects [13].

2.4.2 Growing concern and development of the Marine energy resource and industry

Tides are the source of the moving masses of water which are the foundation of tidal stream energy whose potential is site specific. The diverse energy resources extracted from the ocean comprise of the least investigated sustainable, renewable energy resources (RES) around the Western Indian Ocean, WIO [5], [86]. They have only been examined in a few theoretical studies on renewable ocean energy in the Western Indian Ocean, [34], [37], [45]. Notwithstanding, the under exploitation ocean energy assessments, the Western Indian Ocean research institutes and governments have been consulted by ocean energy corporations which has led to an extremely small (micro) turbine being implemented for a local investment initiative [29].

Ocean energy is increasingly recognised worldwide, specifically on tidal power and OTEC in parts of Indian Ocean where strategic farms have been established in India [32]-[34] and estimations in wave and ocean current assessment schemes for power generation potential evident in South Africa for nonstop energy [20], [26]. Diverse ocean energy sources to be deployed in the Persian Gulf and the Gulf of Oman have been discussed and assessed for use in demonstrating potential for tidal and wave power [3], [35]-[37]. On the opposite shore of the Indian Ocean, significant wave energy resources in Australia have been recognised [38].

The attempt to evaluate the Wales, United Kingdom resource [39]-[41] excluded sites of depth less than 20m, speed less than 2m/s and area less than2 km^2. The report interpretation stated that the UK resource was enormous but the unit cost of energy would be high. The exploitation of marine tidal currents, 1994-1996 in the West Coast of Scotland increased with the inclusion of shallow water sites and speeds >1m/s.

With regard to WIO Africa, considerable potential for OTEC exploration and oceanic biotransformation have been under study since 1983 [39]. In spring, 2011 a first marine wave power device designed for distant area and remote islands conditions was tested in Cape Verde. Diverse ocean exploitation focuses not only on electricity, but also desalination of sea water which has been one of the targets addressed in the ocean energy context of developing countries although it is difficult to quantify the extent of significant developments [24], [34], [40].

From the stand point of increased and progressive growth in the domestic electricity demand and ambitions for renewable energy sources, this project takes an examination of tidal electric energy resource potential along the Kenyan coastline, [20], [35], [40]. The simplest way of predicting tides is therefore to measure the water level (or the tidal currents) over some time, to identify how the different effects interact at the specific location. Each effect may be described by a simple sine function, which can be identified in the measured signal. By determining the harmonic constituents present in the signal, and their magnitudes, accurate tidal pre-dictions for the future can be made. The British, Spanish, and French invested in it with advanced plants evident to date as illustrated in Table 2.3. Five projects commercially have been developed in Europe from 1960-2014 [100].

Table 2.3 Industrial revolution, invention of turbines and design modifications [101].

Invention Publication	Performance	Evolution
John Smeaton, 1759 James Watt, 1750 to 1850 Sir Charles Parsons, 1854 to 1931 Richard Trevithick, 1771 to1883 Professor James Blyth, Scotland, 1887 -1908 Cleveland, 2007	5 to 25 kW turbines in Cleveland, Ohio and Denmark Mills and pumps across Europe, USA, Canada, Africa and Australia	Grain mills Wooden, tide mills, steam mills, Steam engine Dutch mills steel blades, Savonius
La Rance Tidal power station Sihwa Lake Tidal power station Bay of Fundy, Nova Scotia, 1956 Passamaquoddy Tidal, 1961 Royal, Annapolis,1984 Jiangxia, Hangzou EMEC, 2003	France, 1960 to 1966 South Korea, 2011 Swansea Bay in Wales, UK Orkney, Scotland in UK 3.2 MW China, 1985	Tidal barrage Tidal stream generator Dynamic tidal power Artificial lagoons
Engineer Finnish, Georg Savonious and George Darrieus rotors, 1922-1931 Siemens	Modern turbines, 20 kW to 7 MW, Peoples republic of China, USA, Germany, Spain and India	Horizontal, vertical, Oscillating hydro-foils and Venturi shaped shroud

2.4.3 Generic modelling of marine tidal stream resource exploitation

Tidal flow field properties, (height, period, direction, etc.) bathymetric features and foundations (shoaling and refraction) that constrain the flow to increase the magnitude and quality of power are important for design consideration of marine current energy converters

[7], [8], [52]. Tidal current flow impedance, inadequate technical adjustment in the turbine has been observed to increase extreme loading and fatigue [1], [53]. Furthermore, unsteady transportation, geological deposition process and fluid dynamics affect the turbine characteristics which have an effect on converter performance estimates. The University of Edinburgh, UK, assessed the total amount of energy including technical and practical constraints (20.6 TWh per annum), [27]. Potential issues which affect the viability of the resource are, water depth, environmental impact, fluid flow properties, grid connections and transmission, [42].

Despite the prevailing circumstances, the forecasting techniques on the type of data applied in the project can entirely be categorized into two main purposes of long-term and short-term predictions with a focus on planning and operational concepts [43]. The long term prediction reports [43], [44], either applied model identification based techniques or models based on deterministic chaos theory, [45]. The application is almost the equivalent case for most projects deploying artificial intelligent based models [36], [45], [46].

Variation of the velocity profile (spring and neap flows), results in variability of the loadings therefore enlarging the potential shortcoming and minimising the potential accomplishment [47]. The feasibility of commercial tidal stream energy is likely to affect the over-engineering of tidal current projects, [48]. Recent research publications have investigated also the hydrodynamics consequences of marine power generation and considered for example alteration to the flow field, alteration in water surface elevation or disruptions in tidal dynamics, [49], [52].

Indeed, highlighted was that current restrictions upon tidal stream devices, in terms of fatigue, installation maintenance and loading conditions [50], could increase the potential destruction to the tidal turbine and its support structure [51], [52]; therefore, the implications of installation maintenance, turbine design has reasonably become a focus of current research [53], [54]. Furthermore, the downtime, (no generation) could have a sufficiently large effect upon the site viability. Storm conditions that may interrupt maintenance support programs should be considered when selecting potential tidal steam energy sites [1], [102].

Diversity of the spring and the neap flow velocity profile, results in variability to the loadings upon support structures, hence increasing the potential irregularities and reducing overall performance, [47]. The feasibility studies of commercial tidal stream energy presumably experience the over-engineering likely to affect projects viability, maintenance and cost [48]. Recent publications analyse also the hydrodynamics consequences of power extraction and contemplate, either on alteration to the flow field, or alteration in water surface elevation or interruption in tidal dynamics, [49], [52]. Indeed, highlighted was that current restrictions upon tidal stream devices, in terms of fatigue, installation maintenance and loading conditions [50], could increase the potential damage to the tidal turbine and its support structure [51], [52]; therefore, the implications of installation maintenance, turbine design has rightly become a focus of recent research [53], [54]. Additionally, the generation downtime could have a remarkable effect upon the site survival. Storm conditions that may interfere on the progress of maintenance programs should be considered when choosing potential tidal steam energy sites [1].

2.4.4 Current costs

Kenya is yet to establish financial support mechanisms for specifically ocean energy developments. Projected site specific European estimates for 2020 ranged from 0.25 to 0.47 euros/kwh [92a], reflective of capital costs, farm devices, operating costs, capacity factors, commissioning costs, production costs, installation and structure, performance of technology, maintenance, grid, personnel and marketing which are relatively expensive. Tidal energy financial projections are speculative currently until a full-scale tidal farm is developed. The projects devices, auxiliary services and financial framework are provided through government grant schemes, technology developers and the community. The projected costs would probably decrease with deployment, although unpredictable costs on control, operations, monitoring and management would emerge. Combined design and infrastructure construction of ocean energy technologies, e.g. tidal range and tidal stream initiate tremendous cost reduction up to 40% [6].

2.4.5 Tidal Energy Technology

Tidal current energy technologies convert kinetic energy to electricity employing (i) horizontal (76%), vertical (12%), and axes (ii) reciprocating devices, hydrofoils and (iii) screw-like devices and tidal kites outlined in as Figure 2.2. High spatial and temporal resolution is needed for proper planning and the optimization of the design of ocean energy converters [57], [58].

Research and design investment were oriented towards viable commercial projects compliant to environmental benefit and impacts. Efficiency was a technological challenge requiring careful monitoring and planning amidst taking risks. New development and industrial trends on landscape management, company profile, product specification, opportunities and threats seeks marine energy experts for reliable concept implementation. The identification, development and prediction of commercially viable tidal stream technologies when deployed at array scale, address system optimization with improvements in a wide range of supply-chain and infrastructure issues [59].

Design and installation of the horizontal-axis turbines have varied off-shore support structures as shown in Figure 2.3, to overcome hydrodynamic loads, fatigue damage and dynamic response to seabed topographical features. The rotational axes of the horizontal axis turbines are parallel to the water flow direction while those of the vertical axis systems are perpendicular to the water flow. Optimal air-foil shapes over the blade length and the structural design are well suited to pitch mechanism for provision of higher lift and maximum generation torque [60], [62], [63].

The investigation on the current commercial status of the horizontal tidal turbine was promising for a predictable runtime of up to 20 hours per day. Twin rotors design under surveillance [61] had capacity to capture infinite kinetic energy from the tides with 180 degree pitch control for power generated at varied loads during the flood and ebb tide.

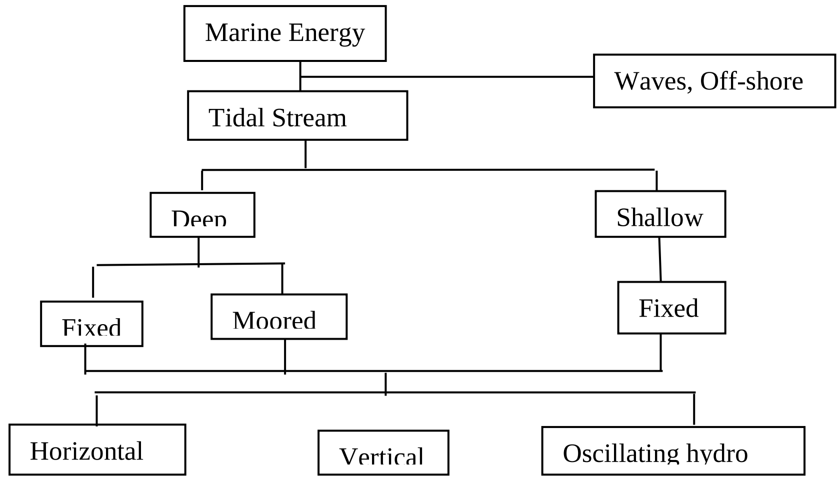


Figure 2.2 Tidal current Technology Development (Prototype Stage) [62], [63]

The power estimated at 1.2 MW to power 1500 homes per day at no primary cost.

2.4.6 Development Stage

The design target for developers is to bring down the marine energy technology costs to make it competitive with other different forms of electricity generation. Prioritizing a specific technology recommendation at different sites with tests been carried out on the technical aspects of the devices' performance in relation to adaptation of site conditions and environmental impact.

Establishment of research test centers for marine devices and energy technology progress are governed by policies in support of and dedicated to deployment acceleration and integration of the renewable energy into the grid, [Appendix D, Figure 1] for an illustration of research and test centers developing diverse technologies with increased reliability and efficiencies [104].

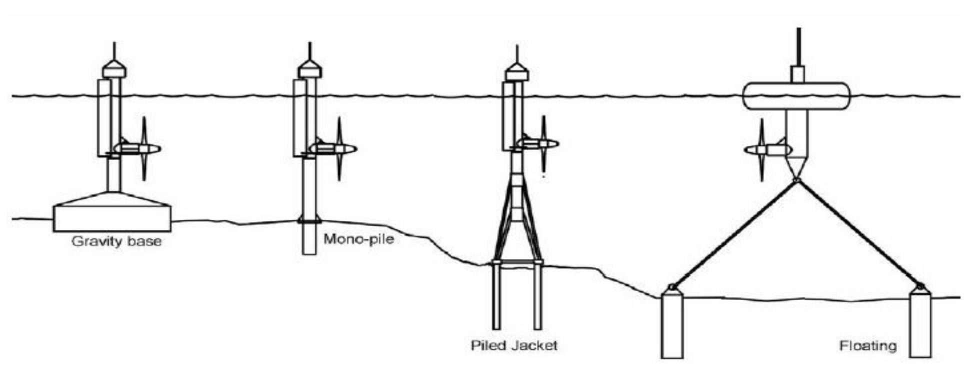


Figure 2.3 Turbine support structures configurations vary with Ocean depth [103]

Technologies have recently advanced significantly and on-going demonstration projects launched in Europe with new devices (approximately 40) been inaugurated between 2006 and 2014. Turbines' functional difference is under investigation and actual deployment demonstrations with next projection being on arrays of turbines' performance, [101], Europe estimated 12 GW minimum from harvestable tidal resources in which deployment projections are in the range of 200 MW by 2020.

2.4.7 Regulatory and Legal affairs aspects for effective marine energy development

Essential supporting legal and regulatory structures affect the evolution of technologies, industries, and environmental strategies with strong links between these affairs emphasized by social sciences research agenda [37]. The UN convention on the law of the sea defines world's oceans' utilization for internal and territorial waters extension beyond its land and air space. The Convention establish the breadth of its territorial sea up to a limit not exceeding 12 nautical miles, measured from baselines determined in accordance with the Convention. Internal water and waterways are on the landward side of the baseline, evident in that no foreign vessels have rite of passage within internal waters.

Ocean energy should uphold the territorial waters encompassing a stretch of up to 22 km (12 nautical miles) from the baseline which is the mean low-water line. Territorial waters are sovereign territory of the state and give the full rights over water, seabed and sub soil [58]. For islands having fringing reefs, the baseline for measuring the breadth of the territorial sea is the seaward low-water line of the reef. The coastal country has the right to set laws and regulate the use of the ocean and its territorial waters. The territorial waters are followed by an exclusive economic zone extending up to 200 nautical miles, with reference to territorial sea baseline from where a country possess the rights to explore, exploit, conserve and manage the natural resources of the water column and seabed, [59]. These laws relate only to bays and coasts which belong to a single State [105].

Most ocean energy devices have and will be installed in territorial waters. Maritime legislation include: foreshore acts, electricity regulations, habitats and birds directive, sea directive and energy directive [40].

2.4.8 Further Research

Harmonization of modelling approaches to achieve appropriateness of approximation, quality assurance of development and the rigor of the verification and validation process of tides and tidal energy resource maps [79]. Modelling approaches are needed for characterization of resource assessment, optimization of technology development and ability to predict the physical phenomenon impact and consequence [56].

Planning, governance, licensing processes and rules in the Ocean energy should be open and comprehensive to marine environmental impacts, protected habitats and nature conservation in order to take into account concerns of new technology. The tidal energy innovation technology is a challenge especially due to alterations in flow patterns, sedimentation, grid connection and physical interactions require modelling efforts, and studies conducted on similar structures in the ocean energy development to contribute to the existing knowledge base profile, [69].

Procedures addressed comparisons of conditions which includes mechanical fatigue, capacity factor influence on energy distribution, interaction and ability to quantify impact on device from channel, and the associated calculation method when designing a turbine for the challenging hydrodynamic environment, [70].

The Indian Ocean is evidenced by gyres, a ring like system of ocean currents due to wind, Coriolis effect, planetary vorticity along with horizontal and vertical friction, which rotate clockwise in the Northern hemisphere and counterclockwise in the Southern hemisphere [45], [107]. The Indian Ocean gyre is one of the major five, [44], composed of two major currents, the Southern Equatorial current and the West Australian current. The northern part of the Western Indian Ocean region is dominated by the monsoons which give rise to reversal of wind and current directions during different seasons as illustrated in Figure 2.4.

The Inter Tropical Convergence Zone, ITCZ, or winds doldrums, is a low pressure belt located north of the equator with effects felt from 5 degrees north of the equator to 5 degrees south of it. It is where the trade winds of the Northern and Southern Hemispheres come together, characterized by convective activity which generates vigorous thunderstorms over large areas [41], [108].

The site specific numerical modeling when validated offers a higher resolution picture of the resource.

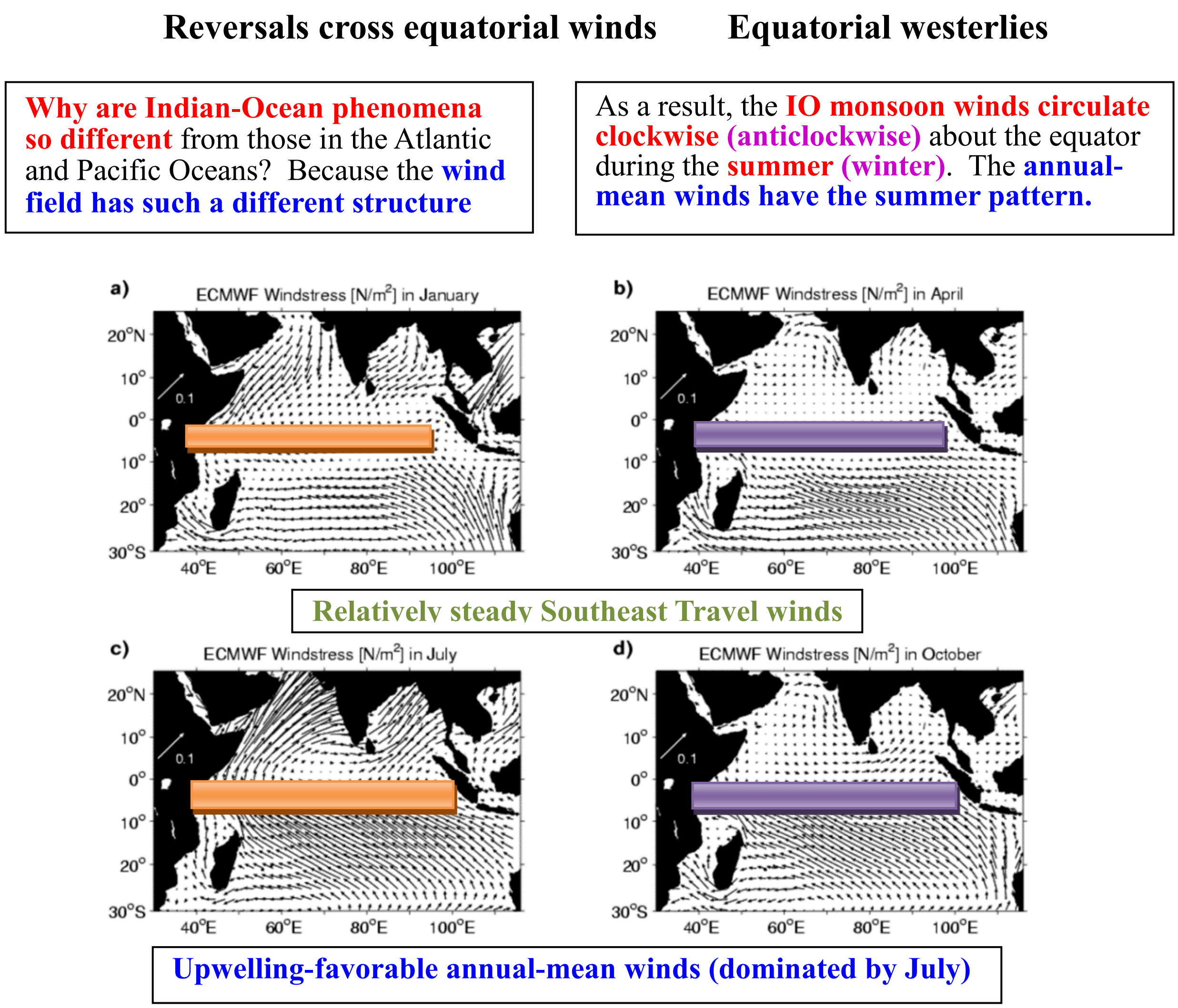


Figure 2.4 Climatological wind forcing [89]

Marine resources and renewable energy exploitation in a sustainable way is a wakeup call for research, design, installation and development of ocean energy technology. There is need to institute adequate evidence on the quantity and accurate assessment of power generation function on the sea flow speed for industrial prediction and development [6], [42], [104].

The concern over climate change has increased dramatically with many legislative bodies worldwide recognizing the need of greenhouse gas emissions' reduction, shifting the attention to sustainable and environmentally friendly energy [6], [28], [95], [49].

2.4.9 Thesis requirements

Data analysis and prediction entailed conversion into appropriate format for employment in Matlab and Excel. Buoy data processing was implemented through the National Oceanic and Atmospheric Administration (NOAA) induction programme during a three months attachment with Kenya Marine Fisheries Research Institute, KMFRI in Mombasa. Band-pass filtering techniques (sub- and super- variations of signals, astronomical parameters, etc.) ensured pre- and post- processing software for scientific data preparation, analysis, plotting and visualization of ocean currents dynamics, [109].

Site selection took stock of steady and continuous waves, current or stream velocity and flow rate (direction, speed, volume and density flow circulation through the channel space and time) [95].

Resource characteristics were dependent on location bathymetry, water depth, geology of sea bed and environmental impacts which were fundamental on device design, the appropriate deployment method needed and cost of installation [93], [110], [112].

Ocean hydrokinetic technology has unique challenges mainly on construction and maintenance costs, resistance to storms and corrosion, with turbines and moorings being submerged in saline water or placed on the sea floor, prevention of marine growth build-up and bubble formation (cavitation in hydraulic turbines). The ocean energy technology engineers and potential developers acknowledge that the aforementioned sources are site specific, [4], [38], [93].

Electrical grid connection is an instrumental infrastructure with sea floor cable design and installation from proposed site to a grid access point. Location of projects, local project investment cost of electricity and the cost of competing sources of electricity helped to compute the viability of an installation [111], [14], [112].

Impacts on the marine environment from the construction, electromagnetic effects from power cables and undesirable emissions, were a significant concern that requires further assessment.

2.5 Summary

Ocean Energy is an emerging technology to create clean and renewable power sources. Statistic displays the tidal energy installed capacity of: China leading with 4.8 MW, United Kingdom, 3.2 MW, Canada 2.5 MW, France 2.25 MW, Netherlands 1.65 MW, South Korea 200 W, Italy 60 W and Sweden 0.0075 MW. Their equivalent consented tidal energy projects of China 0.45 MW, France 6.85 MW, Italy 200 W, Netherlands 1MW and South Korea 1MW as per National Oceanic and Atmospheric Administration, NOAA 10 October 2017.
The primary indicator of a site potential is the annual average power per unit length of wave crest, for example, 30-50 kW/m.

The velocity of the tidal stream and the area intercepted determine the energy extracted similar to wind power extraction. Water is denser than air hence an equivalent power is extracted for smaller areas and at slower velocities. The average velocity determines the site potential of a tidal stream.

Limiting factors for tidal energy integration and commercialization are the ability to:

(1) Design cost-efficient turbine systems that are robust enough to withstand the challenging environmental conditions. This focused on the technology of the device and its direct infrastructure.

(2) Properly address general mechanical and turbine technology fatigue e.g. blade failure and

(3) Find alternative cost-effective turbine installation techniques. [73].

CHAPTER 3: METHODOLOGY

3.1 Overview

This chapter has been divided into three sections as shown in Figure 3.1 where section 1 discusses from first principles, the basic derivation of equations for the ocean wave spectrum namely, energy balance equation, the transport equation, and the radiative transfer equation. Section 2 highlights the numerical scheme applicable in the solution of the energy balance equation and section 3 illustrates the verification of the results [7], [41].

The chapter's objective was to design and develop models applying Excel and Matlab for analysis of tidal current energy and determine the estimated tidal power extracted from the Kenyan Coastline.

The methodology entailed FIVE stages:

1. Resource investigation involves calculation of shear profile and derivation of velocity
2. Technology assessment entails modelling of the conversion technologies that is, horizontal axis turbine
3. Harmonic decomposition determines current amplitudes

The representation on a chart of the tidal datum and the height of the ocean tide entailed:

a) Highest astronomical tide, (HAT) - highest occurring water level under tidal forcing
b) Mean high water Springs (MHWS) - height of an average spring tide high water level
c) Mean high water Neaps (MHWN) - height of an average neap tide high water level
d) Mean sea Level (MSL) - mean water depth at the site
e) Mean low water Springs (MLWS) - height of an average spring tide low water level
f) Mean low water Neaps (MLWN) - height of an average neap tide low water level
g) Lowest astronomical tide (LAT) - lowest occurring water level under tidal forcing

4. Economic model: Estimating electrical output and equivalent power cost
5. Potential hydraulic power

Outline of the Thesis Methodology

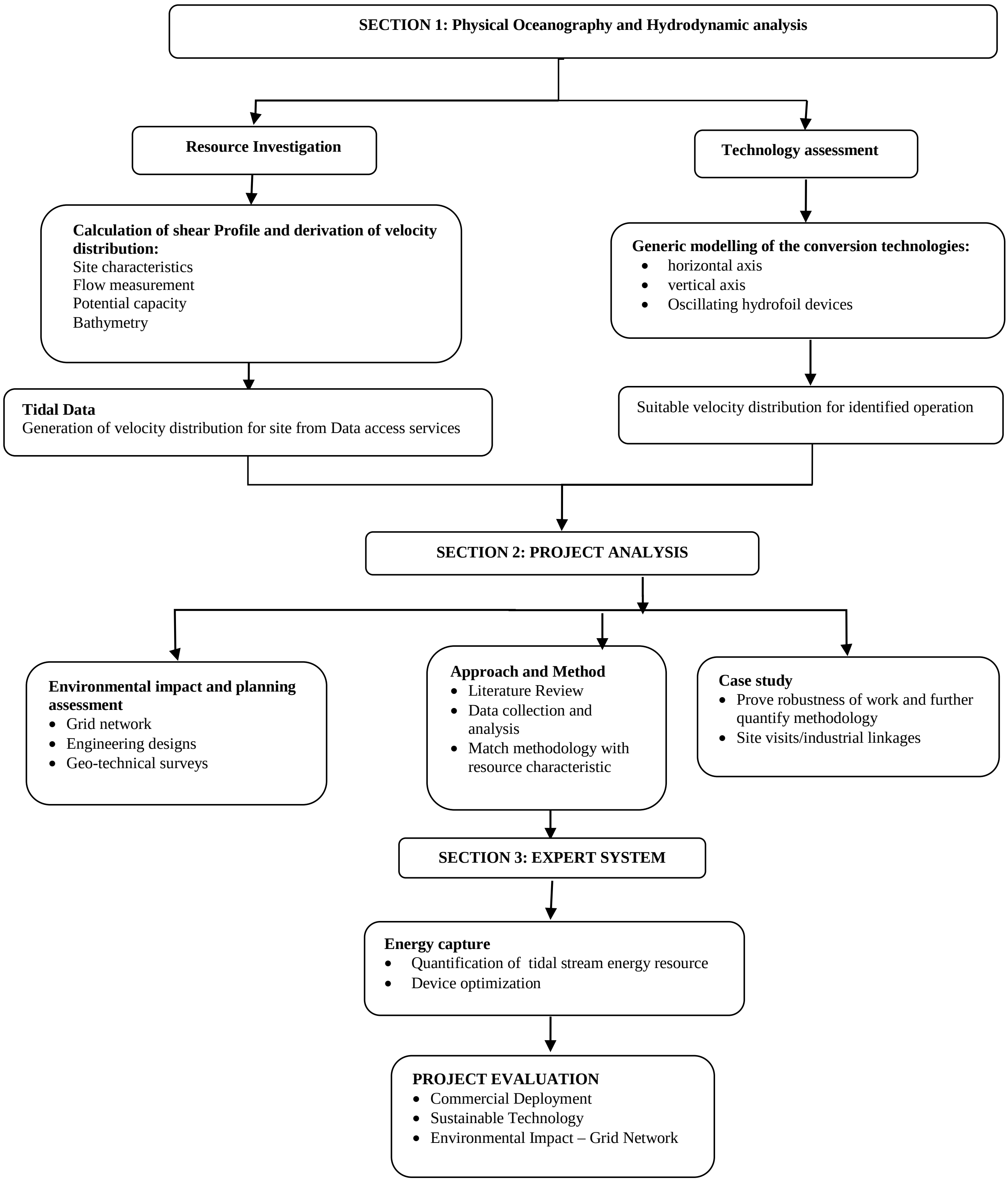


Figure 3.1 Research Methodology Flowchart

3.2 Resource investigation

This thesis presents the fundamental concepts, principles and findings on how the overall marine tidal current resource may be exploited for extraction of electrical energy. The equivalent estimate is determined by the assessment criteria of the harnessing technology, its operation, configuration, the tidal current flow kinetic energy, and adaptation of the tide-generated power to grid network requirements [42].

3.2.1 Understanding physical processes of fluid flow analytically and empirically

The thesis highlighted the need for site specific modelling due to site characteristics such as topography (bathymetry), orography and seabed roughness, Figure 3.2, which affect the flow at a site.

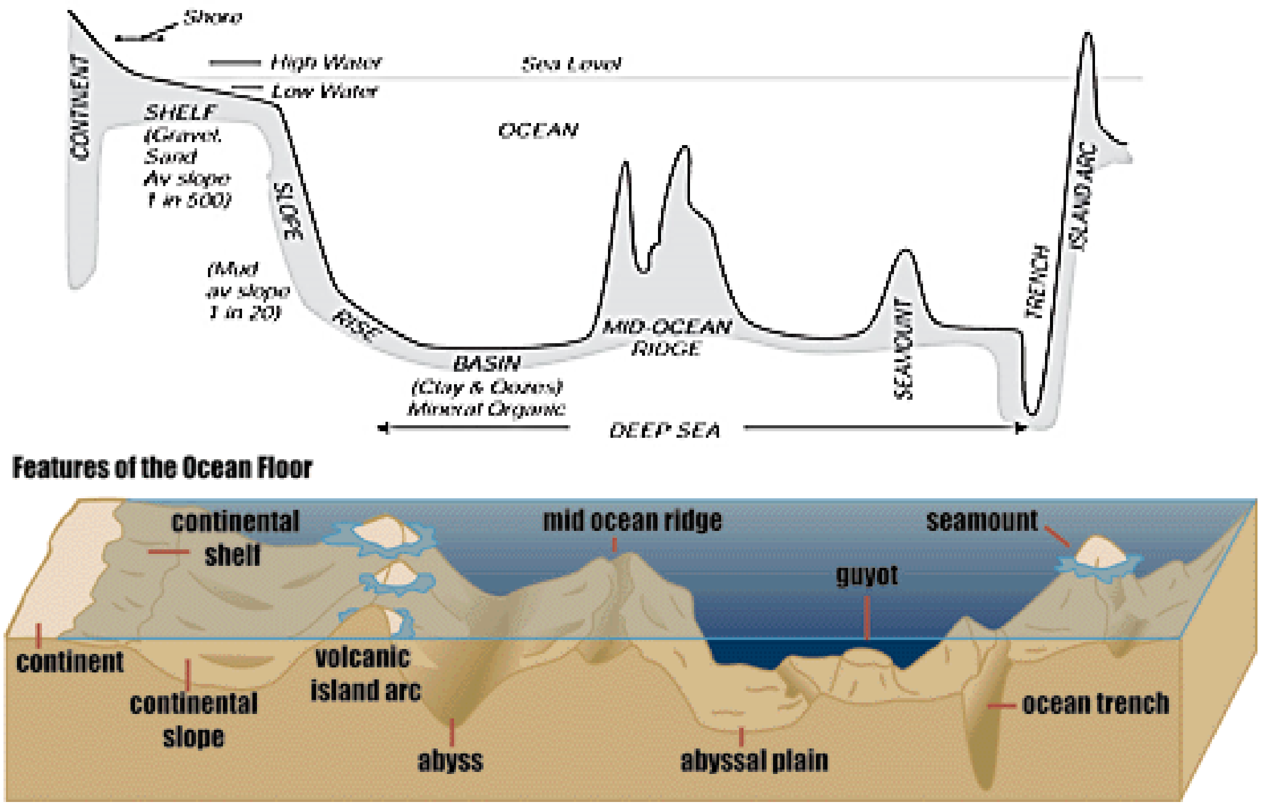


Figure 3.2 Physical features of the Ocean [1998 The Museum of Science]

Open Channel flow, [Table 3-1] – Characteristics of fluid mechanics, within an open conduit (natural or artificial) or channel, is subjected to atmospheric pressure. The other type of flow within a conduit is pipe flow. The two types of flow parameters (hydraulic radius, channel length, and roughness) are similar in many ways, but differ in one respect, the free surface [59].

It was appropriate to consider properties of waves to understand the motion of the water due to tides with respect to energy gradient, pressure and datum. In linear wave theory, the water particles under waves move in closed, orbital paths. In deep water, these paths form circles. Shear stress for a Newtonian fluid is proportional to the velocity gradient,

$$\tau = \mu \frac{du}{dy} \tag{3-1}$$

The proportionality factor μ is viscosity and is the state of being thick, sticky and semi fluid in consistency due to internal friction [43], [44].

Open channels experience variety of forces classified as geometric elements on discharge – depth relationships, velocity, hydrostatic pressure, mass, momentum and energy transfer, which affect the hydraulic behavior of flow. The Reynolds number which is dimensionless classifies the flow to steady and unsteady if criterion used is time, or uniform and non-uniform if criterion used is space, leading to an orderly series of fluid laminar or layers conforming generally to the boundary configuration.

$$\text{Reynolds Number, } Re = \frac{\text{Inertia Force}}{\text{Viscous Force}} \qquad [36]$$

Lower Reynolds numbers exert uniform flow known as Laminar ($Re < 2000$) since any disturbance introduced by irregular boundaries is dampened by viscous forces. For higher Reynolds numbers, the viscous forces are not sufficient to dampen the disturbances introduced to the flow. Minor disturbances are always present in moving water, and at high Reynolds numbers such disturbances will grow and spread throughout the entire zone of motion. Such flow is called turbulent ($Re > 4000$), and water particles in turbulent flow follow irregular paths that are not continuous. A transitional state of flow ($2000 < Re < 4000$) exists between the laminar and turbulent [43], [44].

Fluid flows are classified as laminar, transitional or turbulent. A laminar flow is characterized by smooth, predictable fluid motion, while a turbulent flow is unsteady and chaotic.

3.2.2 Ocean waves and swells

Waves, as illustrated in Figure 3.3, are forward movement of the ocean's water due to the oscillation of water particles, [45], [53]. A water wave as observed in the ocean is the outward manifestation of the transmission of a series of disturbances caused by winds, earthquakes, volcanoes, and landslides [35], [46], [112]

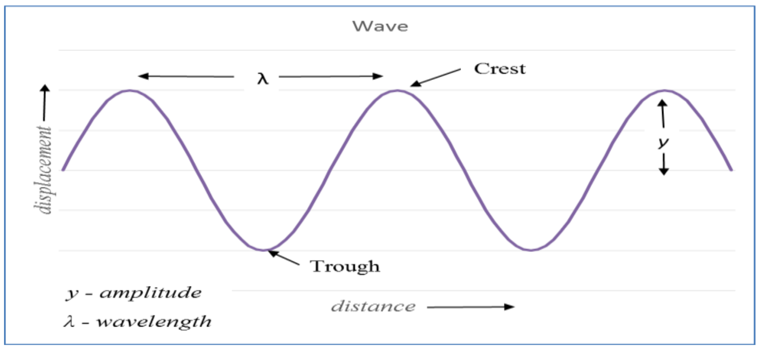


Figure 3.3 Ocean waves [8]

3.2.3 Tidal Resource

Tides are the alternate rising and falling of the waters in relation to vertical height of the sea due to astronomical variation and distribution of forces.

Tidal currents are generated by the rise and fall of the tide, which is accompanied by horizontal movement (flood and ebb) of the waters called Tidal current [45], [48].

According to the Newton's universal law, the gravitational force F_G is given by:

$$F_G = G\frac{m_1 m_2}{r^2} \qquad (3\text{-}2)$$

m_1 *and* m_2, are masses of objects of the celestial bodies, G is the gravitational constant and r is their distance apart. With reference to Figure 3.4, it is evident the sun's gravitational force is much greater than that of the moon, but it can be shown why the ocean tidal force of attraction due to the moon is emphasized [1], [49].

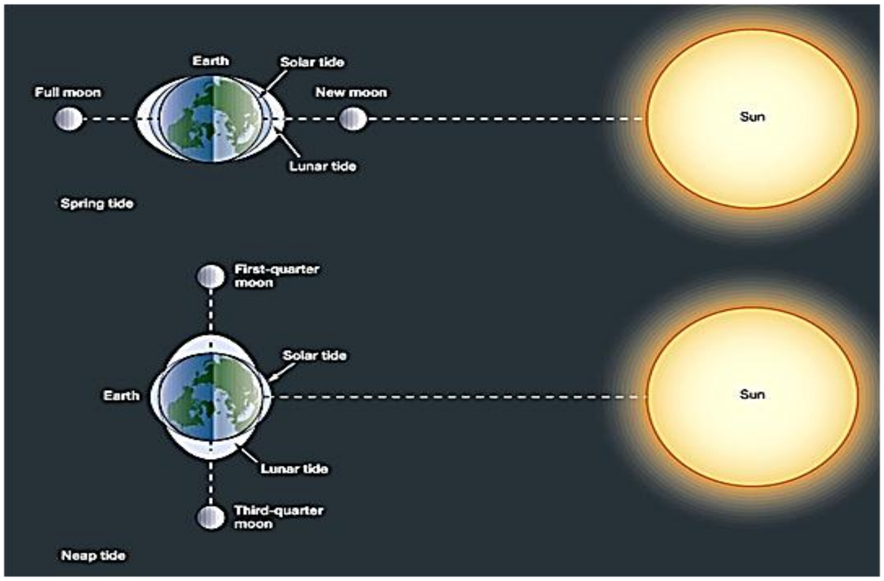


Figure 3.4 spring and neap tides [27]

The motions of the atmosphere are governed by the fundamental physical laws of conservation of mass, momentum and energy. These principles have been applied to a small volume of the atmosphere in order to obtain the governing equations. The forces can be classified as either body (weight forces) or surface (pressure and friction forces) Table 3-3, [5], [50, [122].

Table 3-3: Hydrodynamic forces

Body forces	Surface forces
Gravity, g ; Density, ρ	Stresses
External electric fields	Pressure, P
Magnetism	Hydrostatic
Electric potential	Viscous

Body forces act in the center of mass in a fluid parcel; have magnitudes proportional to parcel mass. Surface forces act across the boundary surface separating a fluid parcel from its surrounding; their magnitudes are independent of the mass of the parcel [5], [122].

3.3 Expressing fluid flow processes mathematically

According to Navier-Stokes equations, on motion of viscous fluid substances, the flow field in three-dimensional movement is determined by the velocity vector $\vec{V} = \vec{V}(x, y, z, t)$ pressure $P(x, y, z, t)$ and temperature $T(x, y, z, t)$. Other variables are salinity and humidity.

Flow speed and power output from observed and theoretical resource data and curves of electrical generation demonstrates comparison for coefficient of power performance in relation to device tip speed ratio.

3.3.1 Basic equations

Assumptions:

1. Newtonian fluid [51]
2. Constant viscosity [52]
3. Incompressible flow [47], [114]

Sigma coordinate equations (3-3) to (3-5) are based on the transformation illustrated in Figure 3.5, the depth uniformly divided into boundary conditions ranging from σ = 0 at z = η, to σ = -1 at z = H

$Z = z(x, y, \sigma, t)$, a free surface datum whose range is positive above η and negative below H (3-3)

σ represents a scaled pressure level

$$\sigma = \frac{z-\eta}{H+\eta} \text{ ranges from } \sigma = 0 \text{ at } z = \eta \text{ to } \sigma = -1 \text{ at } z = H \quad (3\text{-}4)$$

$$\text{depth of flow, } D = H + \eta \quad (3\text{-}5)$$

$$\text{bottom topography, } H(x, y) \text{ surface elevation, } \eta = (x, y, t)$$

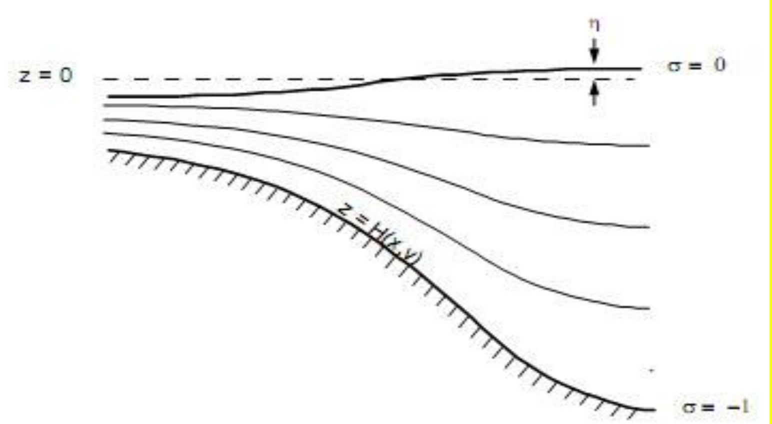


Figure 3.5 Typical sigma coordinates [2], [3], [54]

3.3.2 Continuity equation (conservation of mass)

$$\text{Divergence of a vector field, } \left(\text{div}\,\vec{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)$$

(3-8a)

$$\text{Gradient of a scalar field } \left(\text{grad}\,\rho = \frac{\partial \rho}{\partial x}\bar{\imath} + \frac{\partial \rho}{\partial y}\bar{\jmath} + \frac{\partial \rho}{\partial z}\bar{k}\right) = \nabla\rho \quad \text{[vector field]}$$

(3-8b)

$$\text{Del or nabla, } \nabla = \frac{\partial}{\partial x}\bar{\imath} + \frac{\partial}{\partial y}\bar{\jmath} + \frac{\partial}{\partial z}\bar{k}$$

(3-8c)

Conservation of energy states that energy is neither created nor destroyed for constant mass: Initial steady state position + potential energy + kinetic energy = 0

$$\frac{\partial \rho}{\partial t} + \vec{V}\text{grad}\,\rho + \rho\,\text{div}\,\vec{V} = 0 \implies \frac{D\rho}{Dt} + \rho\,\text{div}\,\vec{V} = 0$$

(3-9)

Considering horizontal Cartesian coordinates of an incompressible fluid with the height dimensions in relation to datum and elevation boundaries considered:

$$\frac{\partial Du}{\partial x} + \frac{\partial Dv}{\partial y} + \frac{\partial w}{\partial \sigma} + \frac{\partial \eta}{\partial t} = 0$$

(3-10)

3.3.3 Momentum/motion equations:

Mass multiplied by acceleration is equal to the sum of the forces that act on a volume unit.

$$\frac{D\vec{V}}{Dt} = -\frac{\nabla P}{\rho} + g\omega - \left(2\Omega \times \vec{V}\right) + \mathcal{F}_r$$

(3-11)

G represents modification of the gravitational force which depends on location and balance the attraction and repulsion forces contributed by all of the matter in the universe in other words cosmological constant, ω.

P represents pressure, $\left(2\Omega \times \vec{V}\right)$ Coriolis force; and $\mathcal{F}_r$ friction force in x, y and z dimensions:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = \frac{-1}{\rho}\frac{\partial P}{\partial x} + (2\Omega \times V\sin\varphi) + \mathcal{F}_x$$

(3-12)

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = \frac{-1}{\rho}\frac{\partial P}{\partial y} - (2\Omega \times U\sin\varphi) + \mathcal{F}_y$$

(3-13)

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = \frac{-1}{\rho}\frac{\partial P}{\partial z} + (2\Omega \times U\cos\varphi) - g + \mathcal{F}_z$$

(3-14)

Considering horizontal Cartesian coordinate:

$$\frac{Du}{Dt} + \frac{1}{\rho}\frac{\partial P}{\partial x} - fv = \mathcal{F}_x \tag{3-15}$$

$$\frac{Dv}{Dt} + \frac{1}{\rho}\frac{\partial P}{\partial y} - fu = \mathcal{F}_y \tag{3-16}$$

$$\frac{1}{\rho}\frac{\partial P}{\partial z} + g = 0 \tag{3-17}$$

3.3.4 Energy equation:

Bernoulli's principle on conservation of energy, states that for an inviscid flow of a non-conducting fluid, an increase in speed occurs with a decrease in pressure or decrease in the fluid's potential energy, equation (3-18).

$$P_1 + \frac{1}{2}\rho V_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho V_2^2 + \rho g h_2 \tag{3-18}$$

Inviscid flow is the flow of an ideal fluid that is assumed to have no viscosity. In fluid dynamics viscous effects can be neglected.

$$\rho\vec{g} - \nabla.\vec{P} + \mu\left(\frac{\partial^2\vec{V}}{\partial x^2} + \frac{\partial^2\vec{V}}{\partial y^2} + \frac{\partial^2\vec{V}}{\partial z^2}\right) = \rho\frac{D\vec{V}}{Dt} \Longrightarrow \rho\vec{g} - \nabla.\vec{P} + div\,\vec{\tau} = \rho\frac{D\vec{V}}{Dt} \tag{3-19}$$

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = F_x - \frac{1}{\rho}\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{3-20}$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = F_x - \frac{1}{\rho}\frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{3-21}$$

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = F_x - \frac{1}{\rho}\frac{\partial P}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{3-22}$$

Newton's laws were applied with consideration to certain apparent forces namely centrifugal force, Coriolis (Ω) force being included among the reacting forces, [58].

3.4 Power conversion principle

The aerodynamic lift principle is applicable. When the volume of seawater flows across and past a turbine blade, the difference in the pressure on either sides of the blade produces a lift force, causing the rotor to rotate and cut across the water mass [59].

3.4.1 Betz equation and criterion

Carnot cycle efficiency in thermodynamics suggests that work cannot extract all the energy from a given source. The limited efficiency of a fluid turbine is caused by braking of the fluid from its upstream speed, U_u to its downstream speed U_d and allowing a continuation of the flow regime [59]

The maximum optimal value of performance coefficient C_p is calculated as follows:

$$C_p = \frac{\text{extractable power, } P}{\text{kinetic power,} W}$$

(3-23a)

Assuming a uniform flow rate through the turbine and beyond, the resistance can be given as:

$$b = \frac{U_d}{U_u} \text{ is equivalent to interference parameter}$$

(3-23b)

As the downstream velocity increase in the expectation of increasing the tidal power extracted, the tube area reduces in size. The maximum velocity exerted by the rotor according to Betz limit and Euler's theorem can be derived as follows:

$$F = ma = m\frac{dv}{dt} = \rho SV(U_u - U_d) \quad \text{(3-24a)}$$

Where S = area swept by the turbine blade

$$P = \frac{dE}{dt} = F\frac{dx}{dt} = FV \quad \text{(3-24b)}$$

E = energy

Extractable power, $FV = \rho SV^2(U_u - U_d) = \rho SV^2 U_u(1 - \frac{U_d}{U_u})$ (3-24c)

$$\frac{1}{2}(U_u + U_d) = V \quad \text{(3-24d)}$$

Kinetic power, $P = \frac{dE}{dt} = \left(\frac{1}{2}mU_u{}^2 - \frac{1}{2}mU_d{}^2\right) = \frac{1}{2}\rho SV(U_u{}^2 - U_d{}^2)$ (3-24e)

$$P = \left[\frac{1}{4}\rho S(U_u + U_d)U_u{}^2\left(1 - \frac{U_d{}^2}{U_u{}^2}\right)\right]$$

(3-24f)

$$P = \frac{1}{4}\rho SU_u^3\left[\left(1 - \left\{\frac{U_d}{U_u}\right\}^2 + \frac{U_d}{U_u} - \left\{\frac{U_d}{U_u}\right\}^3\right)\right]$$

(3-24g)

$$C_P = \frac{P}{W} = \frac{\frac{1}{4}\rho S {U_u}^3 (1-b^2)(1+b)}{\frac{1}{2}\rho S {U_u}^3}$$

(3-25a)

$$C_p = \frac{1}{2}(1-b^2)(1+b)$$

(3-25b)

C_p is then at η = 59.3% at $b = \frac{1}{3}$, Figure 3.6. There are assumptions such as the neglect of radial flow at the turbine which has small effect on the final limiting result. The additional losses in efficiency for a practical fluid turbine are caused by the viscous and pressure to the fluid flow by the rotor and the power losses in the transmission and electrical system.

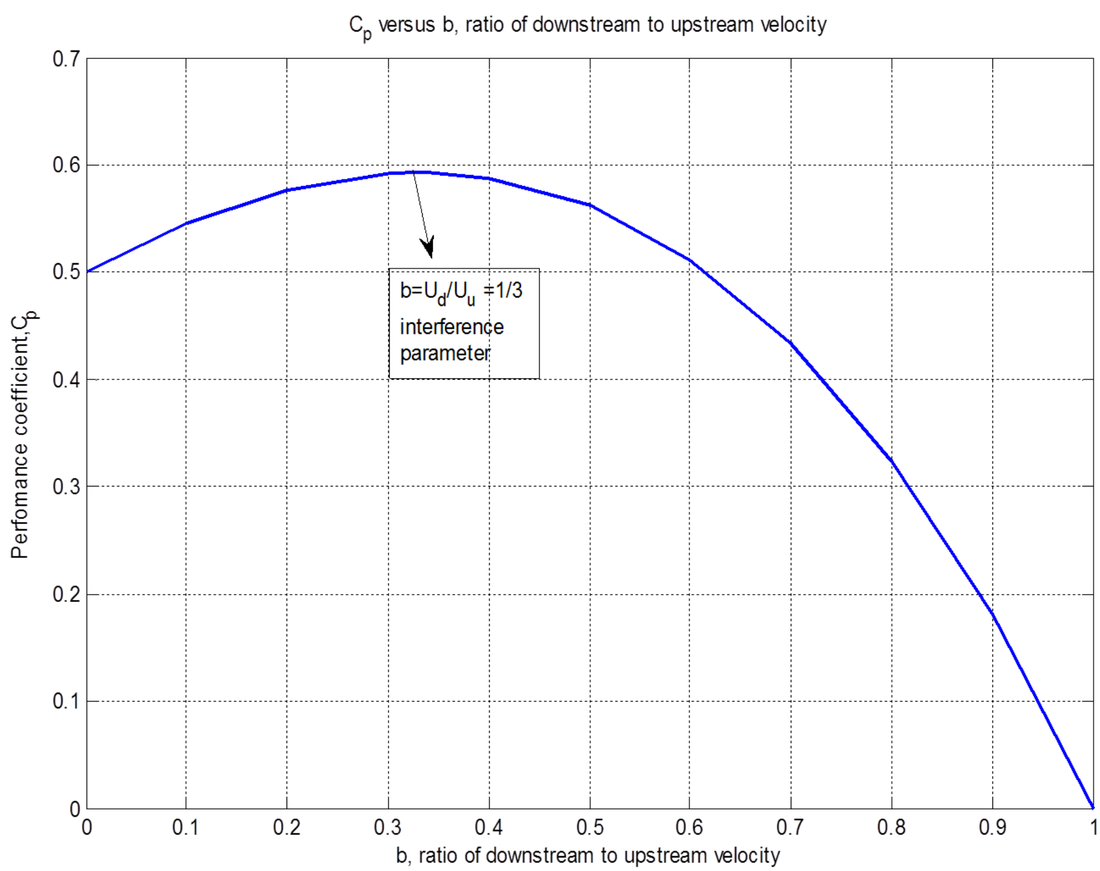


Figure 3.6 C-p versus ratio of upstream to downstream velocity, b

3.4.2 Implication of Betz equation

There must be a fluid speed change from the upstream to the downstream in order to extract energy from the fluid, infact by braking when applying a horizontal fluid turbine. [112]

3.4.3 Tip Speed ratio

If the rotor of the turbine spins too slowly, most of the fluid will pass straight through the gap between the blades, therefore giving it no power.

If the rotor spins too fast, the blades will blur and act like a solid wall to the fluid.

Rotor blades create turbulence as they spin through the fluid especially if the next blade arrives very fast relative to that turbulent fluid, preferably better to slow down or regulate the blades' speed.

The turbines must be designed with optimal tip speed ratio to extract the maximum amount of power from the fluid as illustrated in Figure 3.7 [65], [101]:

$$\text{TSR } (\lambda) = \frac{\text{Tip speed of Blade}}{\text{fluid speed}} \quad \backslash \tag{3-26}$$

$$\text{Tip speed of Blade} = \frac{2\pi r}{\text{rotation time T}} \tag{3-27}$$

If TSR<1 there is a lot of drag, but if TSR>1, there is a lift involved which make the blades spin faster than the fluid speed. For maximum power output, it has been empirically proven [68] [99], [106]

$$\text{TSR } \lambda \text{ (maximum power)} = \frac{4\pi}{n} \approx 6 \; to \; 8 \; for \; n = 3 \tag{3-28}$$

n = number of blades

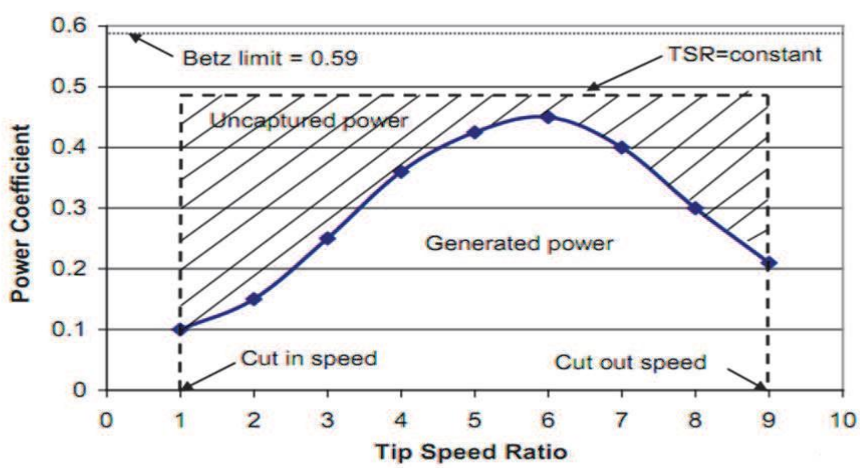


Figure 3.7 Power coefficient as a function of TSR for a two-bladed rotor [11], [55]

Sensors mounted on the nacelle detect the seawater direction, and a yawning mechanism automatically orientates the nacelle and the rotor to face the flow as shown in Figure 3.8. The rotational motion of the rotor is transmitted via the gear box to the electric generator. The output power or torque depends on (i) turbine speed, (ii) rotor blade tilt, (iii) rotor blade pitch angle (iv) size, shape and area of turbine, (vi) rotor geometry – horizontal or vertical and (vii) fluid speed.

A mathematical model to compute relationship between the output power and the various variables would be essential to obtain turbine characteristics in relation to operation, control and performance.

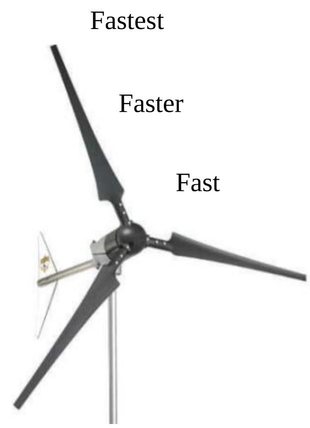


Figure 3.8 The further away from the center, the faster the blades spin [68]

3.5 Tidal Energy Modelling

Inadequate lead researchers of data and control-system structures on wind, wave, and tidal energy in modelling simple conversion systems, almost compromise the analytical results. There must be a tidal speed change from the upstream to the downstream in order to extract energy from the medium; in fact by braking using a turbine. Turbine efficiencies demonstrate that extracted power is $\frac{16}{27}$ of the tidal speed [68].

3.5.1 Tidal Currents Power System

Tidal current electrical energy extraction devices from the kinetic motion of water, equivalent to the movement of air are illustrated in Figure 3.9. These tidal currents are often enlarged around beaches. The tidal currents power system general scheme analysis is summarized in sections (3.61) to (3.67).

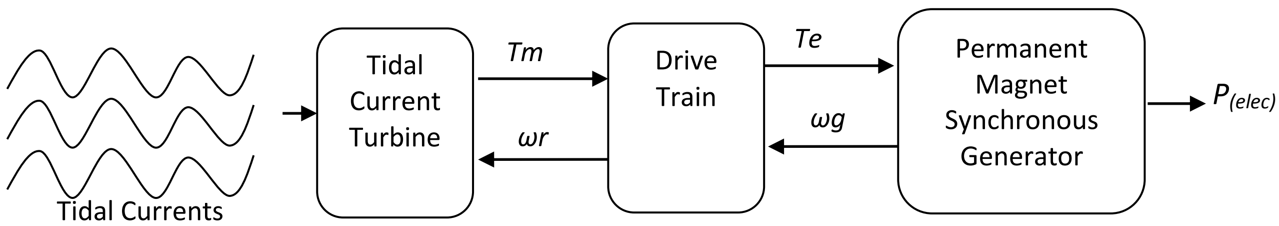


Figure 3.9 Tidal current energy systems

The turbine converts the kinetic energy of the tidal currents into mechanical energy represented in the form of a mechanical torque T_m that controls the drive train with the generator angular speed ω_g producing electrical torque T_e that drive the generator and rotor angular speed ω_r controlling the tip speed ratio of the turbine [65], [71].

3.5.2 Tidal Current Speed Profile

The gross energy content of tidal and marine currents are periodic horizontal flows of water accompanying the rise and fall of the tide. They were modelled as a harmonic series governed by a linear set of equations as expressed in [4], [73].

$$v(t) = \sum v_i \sin(2\pi f_i t + p_i) \tag{3.29}$$

Where v_i is the amplitude, t is the time, and p_i is the phase for the $i-th$ harmonic. Each harmonic is defined by its angular frequency in solar hours [5], [73].

A Simulink model to determine the five harmonics of a tidal model Figure 3.10a and the equivalent speed profile of the tidal currents (b) is shown in Figure 3.10b:

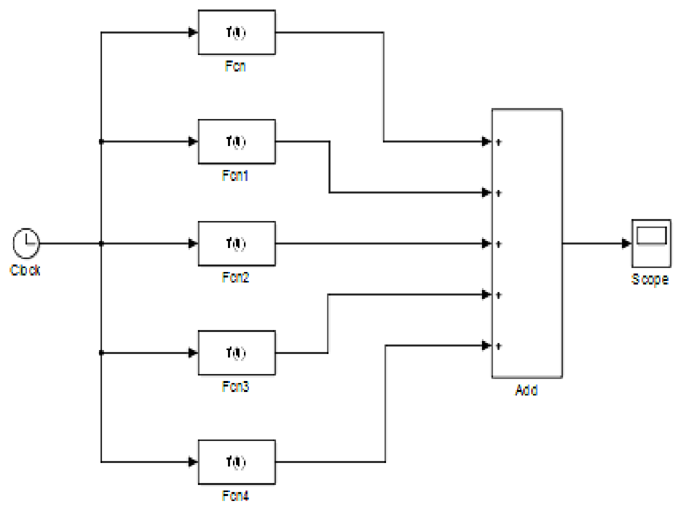


Figure 3.10a Simulink model to determine the five harmonics of a tidal model

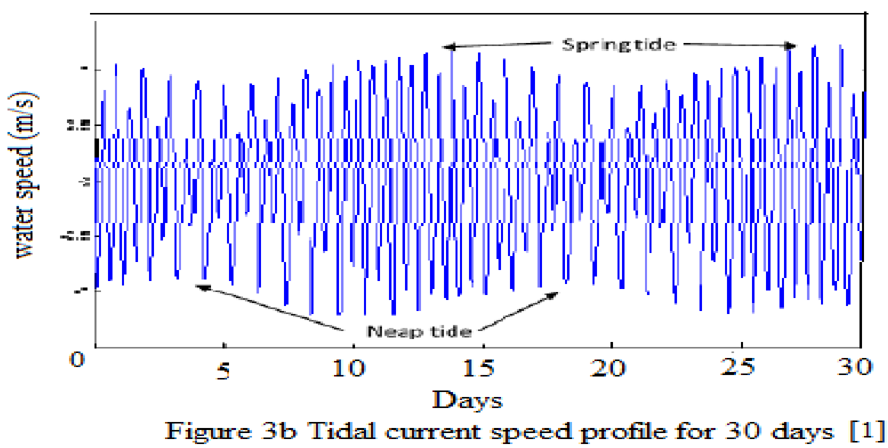


Figure 3.10b Fluid speed profile implementation in Simulink [72]

Two spring tides are evident during the new and full moon and two neap tides at times of first and last quarter of the moon a profile which repeats over all months in the year.

3.5.3 Tidal Current Power

The amount of electric power extracted from the moving water depends on the turbine design. Power extracted from tidal currents is given by [3]:

$$P_{avg} = 0.5\rho A v^3 \text{ watts} \tag{3-30}$$

ρ is the volumetric density of the Ocean water (1027 kg/m^3 at 27^{o}C)

A is the surface area (Area $= \pi R^2$) swept by the Rotor blades in m^2

v is the filtered ocean current velocity at the hub of the turbine or average velocity of the ocean water through the surface A in m/s.

The actual or available power harnessed can be expressed as:

$$P_{act} = 0.5\rho C_p(\lambda, \beta) A v^3 \text{ watts} \tag{3-31}$$

Where the power coefficient, C_p (a function of the tip speed ratio, λ and the turbine blade

pitch angle β) is the ratio of the actual power the turbine can extract from the ocean water flowing through the turbine, to the theoretical power in the flowing water.

The tip speed ratio may be expressed as

$$\lambda = \frac{R\omega_r}{v} \tag{3-32}$$

Where, R is the radius of the turbine rotor or blade length in metres

ω_r is the angular speed of turbine rotor in rad/s [75].

β is the angle between the plane of rotation and the blade rotational chord.

The coefficient of performance of the turbine is not constant. However, generic equations can be modelled to determine its characteristics, as shown in (3-35), (3-36)

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda_i}} + C_6\lambda \tag{3-33}$$

$$\lambda_i = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3-34}$$

Where, λ_i , is the next value of λ, C_p cannot exceed 0.593, Betz 's limit) [6], [67] which reflect to various hydrodynamic losses that depend on the rotor.

The C_p equation is a modified combination of the efficiencies of all the subsystem components with their coefficients, equations (3-34) to (3-36).

The stream electrical power that a tidal turbine extracts is less than the power captured due to generator and gearbox efficiencies:

$$P_m = \eta_G \eta_D c_p(\lambda, \beta)\frac{\rho A}{2} v^3 \text{ watts} \tag{3-35}$$

$P_m =$ Mechanical output power of the conversion turbine (W)

η_g = generator efficiencies range from 50% to 80% high quality grid conneced model

η_D = gearbox efficiencies are typically 90 − 95%

The amount of hydrodynamic torque, T_W rad/s, is given by the ratio between power extracted from the tidal currents, P_{Blade} and the turbine rotor speed, ω_m [76], as follows:

$$\text{Rotor torque}, T_w = \frac{P_{Blade}}{\omega_m} \tag{3-36}$$

$$T_w = \frac{c_p(\lambda,\beta)\frac{\rho A}{2}v^3}{\omega_m} = \frac{1}{2}\cdot\frac{c_p(\lambda,\beta)\rho\pi R^2 v^3}{\omega_m} \tag{3-37}$$

Equation (3-36) can be normalized in the per unit p_u system [77], as:

$$P_{m\_pu} = k_p c_{p\_pu} v_{fluid\_pu}^3 \tag{3-38}$$

P_{m_pu} = Per unit power with reference to density and area

$c_{p_{pu}}$ = Performance of coeffient in pu of the maximum value of c_p

$v_{fluid_{pu}}$ = Ocean water speed in per unit of the base water speed. The base water speed is the mean value of the expected ocean water speed in (m/s)

k_p = Power gain for $c_{p\_pu} = 1$, and $v_{fluid\_pu} = 1\ pu$, k_p is less than or equal to 1

ρ can be expressed as a function of the turbine elevation above sea level H

$$\rho = \rho_o - 1.194 \times 10^{-4} \cdot H \tag{3-40}$$

The coefficients $C_{1\text{-}6}$ in equation (3-34) were expressed as shown in Table 3-4.

Table 3-4 Tidal power coefficients

c_1	c_2	c_3	c_4	c_5	c_6
0.5176	116	0.4	5	21	0.0068

Computed power coefficient, $C_p(\lambda,\beta)$ characteristics analysis involved equations (3-34), (3-35) and Table 3.5 for a given rotor diameter, rotor speed and various blade pitch angles, β,

Table 3-5 Derivation of Tidal power coefficients, *Cp*

When $\beta = 0°$

λ	0	5	10	15
λ_i	0	6.06	15.38	31.58
Cp	0	0.263	0.404	(-0.137)

When $\beta = 5°$

λ	0	5	10	15
λ_i	0.4	0.5443	1.4	15.466
Cp	0	0.211	0.068	0.781

When $\beta = 10°$

λ	0	5	10	15
λ_i	0.8	5.32	10.804	15.809
Cp	0	0.1619	0.1967	0.1819

When $\beta = 15°$

λ	0	5	10	15
λ_i	1.2	6.2	11.2	16.2
Cp	0	0.61	0.025	-0.389

When $\beta = 20°$

λ	0	5	10	15
λ_i	1.6	6.6	11.6	16.6
Cp	0	0.0983	-0.186	1.561

The $C_p - \lambda$ characteristics for changing values of the pitch angle β show that C_p has its maximum value at one particular value of λ for a specific blade pitch, Figure 3.11.

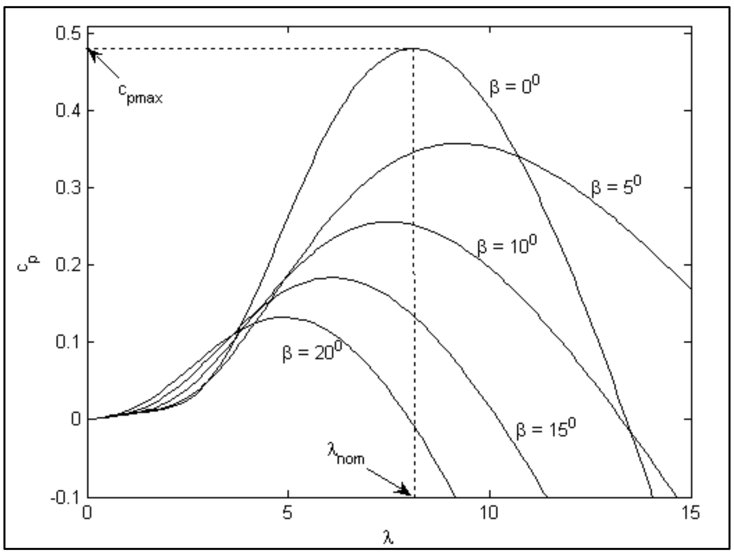


Figure 3.11 C_p max = 0.48 [79] achieved for β = 0 degree and λ = 8.1 [4]

Hence, by maintaining λ at this optimum value, the maximum C_p can be maintained dependably, and thereby extract the maximum power from the turbine as shown in Figure 3.12.

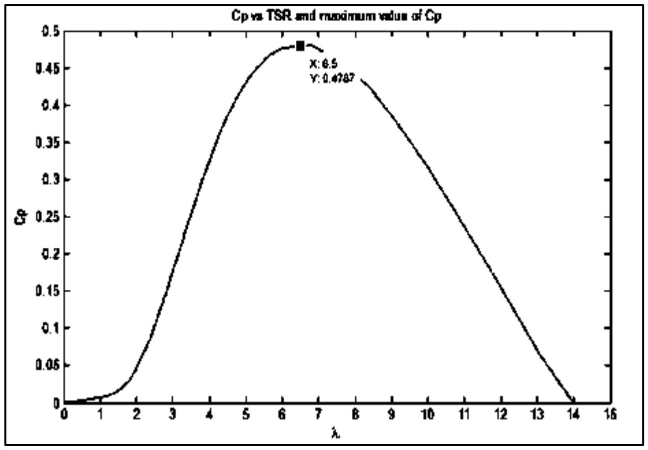


Figure 3.12 Power coefficient relation with tip speed ratio(λ), with β = 0 [4]

The maximum value,$C_p\ max \approx 0.48$, is achieved at $\beta = 0$ degree and for $\lambda = 6.5$ Figure 3.12, which shows that this particular value of λ is defined as the nominal value ($\lambda\ nom$). For maximum power point tracking of the water currents, it is necessary to adjust the rotor speed with the optimum value of λ ($\lambda\ nom$).

The equations (3-32) to (3-34) were implemented in Matlab/ Simulink as illustrated in Figure 3.13 and Figure 3.14 with the hydraulic energy captured by the turbine transmitted to the generator.

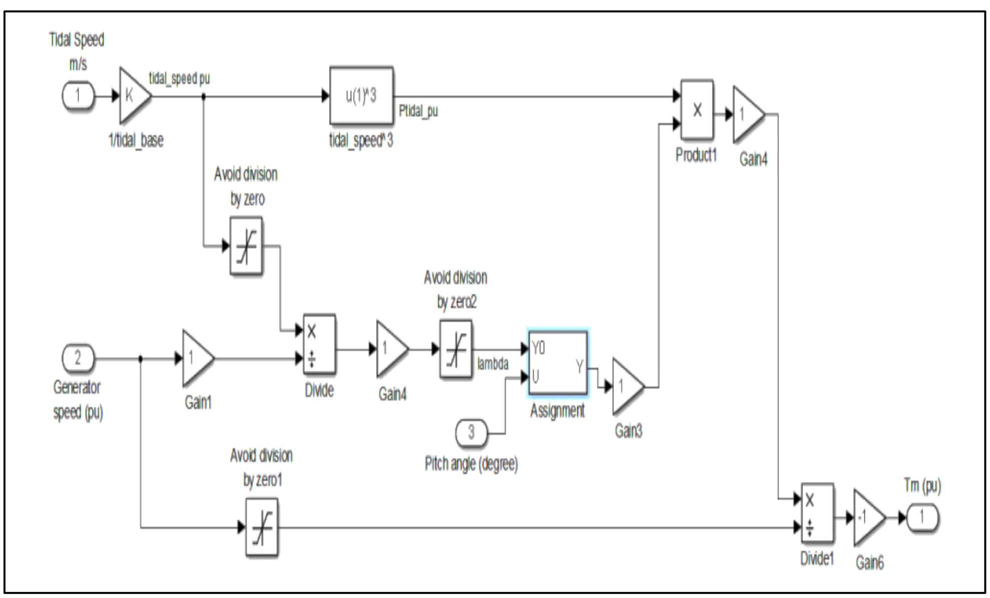


Figure 3.13 Matlab/Simulink tidal current turbine model coefficient of performance characteristics

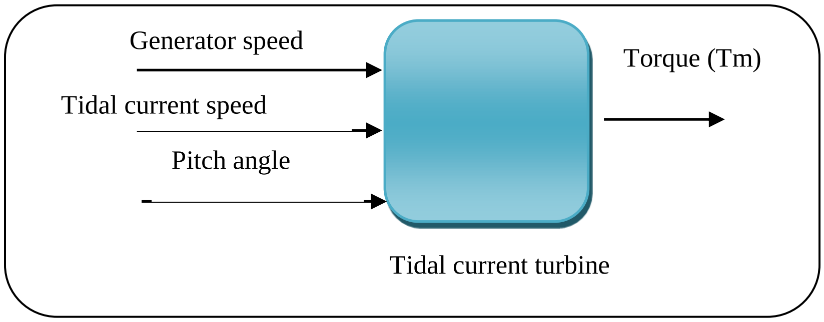


Figure 3.14 Generator parameters

Input parameters to the tidal current turbine are generator speed, tidal current speed and pitch angle while the output is the torque which is given to drive the generator. Figure 3.15 represent the simulation and results of power coefficient of power versus tip speed ratio characteristics for several blade pitch angles [76], [112].

Similarly Figure 3.15 represents coefficient of power for different water speeds, coefficient of torque versus tip speed ratio, and rotor mechanical power curves for various water speeds.

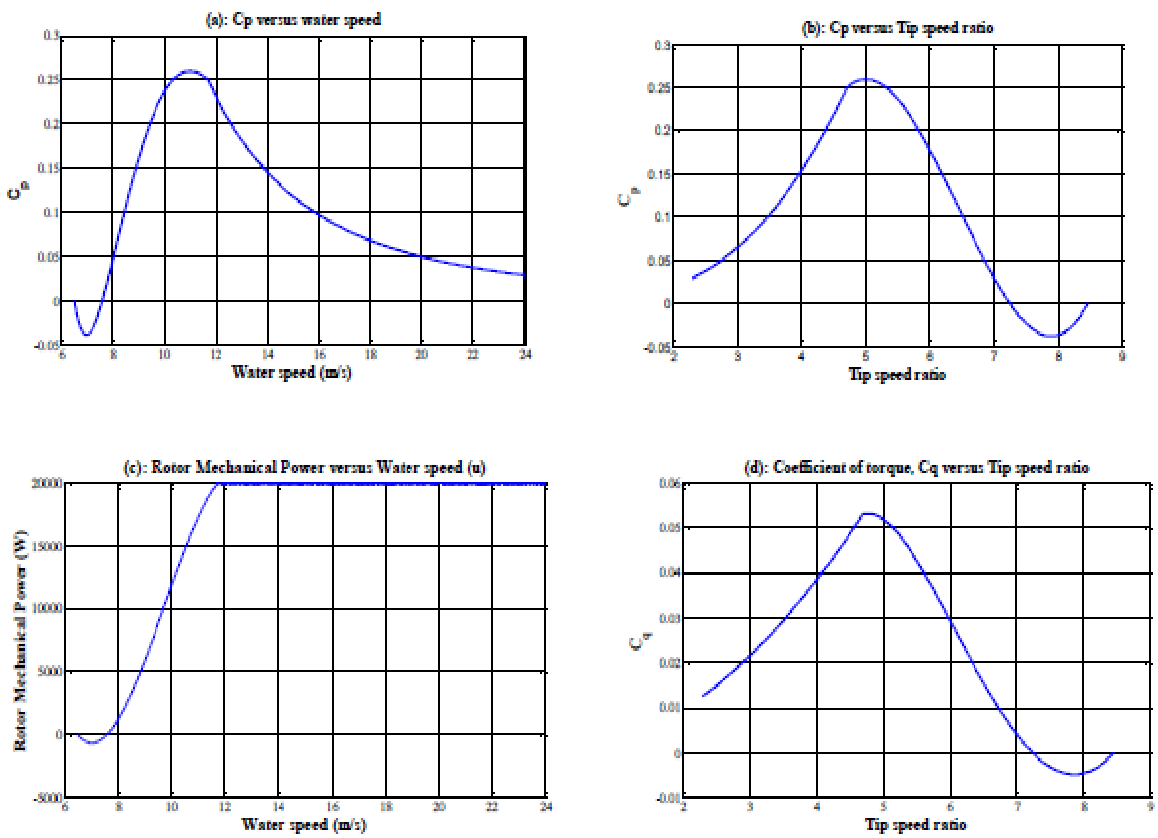


Figure 3.15 Performance Coefficient Graphs, Appendix (A)

The flow field model, Figure 3.16 with specifications given in Table 3-6 and the power curve shown in Figure 3.12 demonstrates optimum power extraction analysis of the turbine with rotor blades geometry, water velocity and efficiency as interpolated coefficient performance functions. Tidal stream turbines classification depends on blades connection, support structure, rotor and drive train configurations. Additional classification parameters are turbine axis direction and diverse pitch in terms of variable, controlled and fixed cases. Rotor configurations include axial- or cross-, open- or ducted. Simple construction is preferable with minimum moving sections, scalability (diameter versus MW rated power generation) and self-contained with no seals and no gearbox needed. No seals mean there are no minimum or maximum depths. This concept permits in fact the minimization of maintenance requirements. The main advantage of the referenced OpenHydro turbine is the ability to operate in bidirectional tidal flow and saving marine life [7].

Table 3-6 Flow field model specifications

Rotor Diameter	15m	Rated power	1.5 MW at v = 2.5 m/s
Cut in Speed	0.7m/s	Output power	11KV AC, 50-60 Hz-3-φ

As can be seen from Figure 3.16, the extracted power was limited to 1.5 MW when the tidal current speed exceeds the 2.57 m/s speed range by the power control strategy [81].

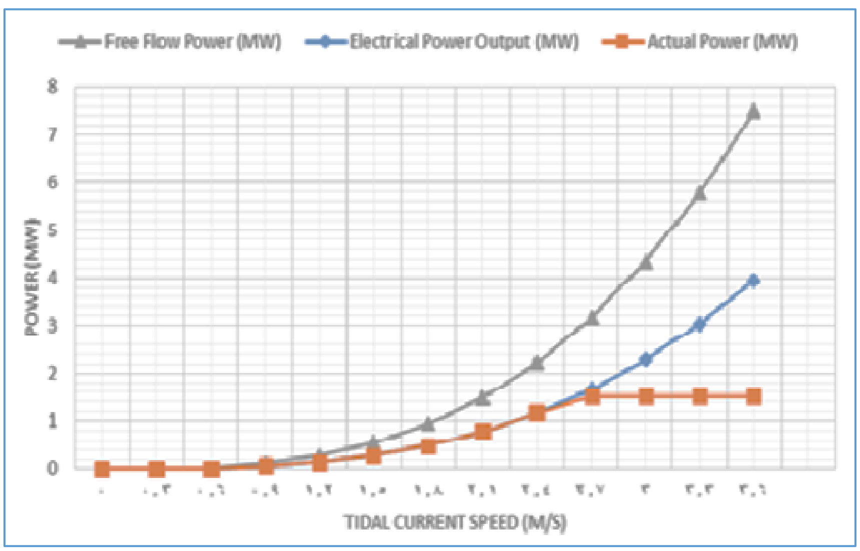


Figure 3.16 Open Hydro power curves with tidal current speed [2]

The generator rated power is 1.52 MW.

3.5.4 Drive Train

Indirect drive train generally consists of low-speed shaft, connected to the turbine hub, speed multiplier and high-speed shaft, motivating the electrical generator. Direct drive transmission (i.e. the generator and the rotor are coupled on the same shaft without gearbox and speed multiplier) is used in case of multi pole synchronous generator. Mathematical model block diagram connecting the drive train in Matlab/Simulink is illustrated in Figure 3.17.

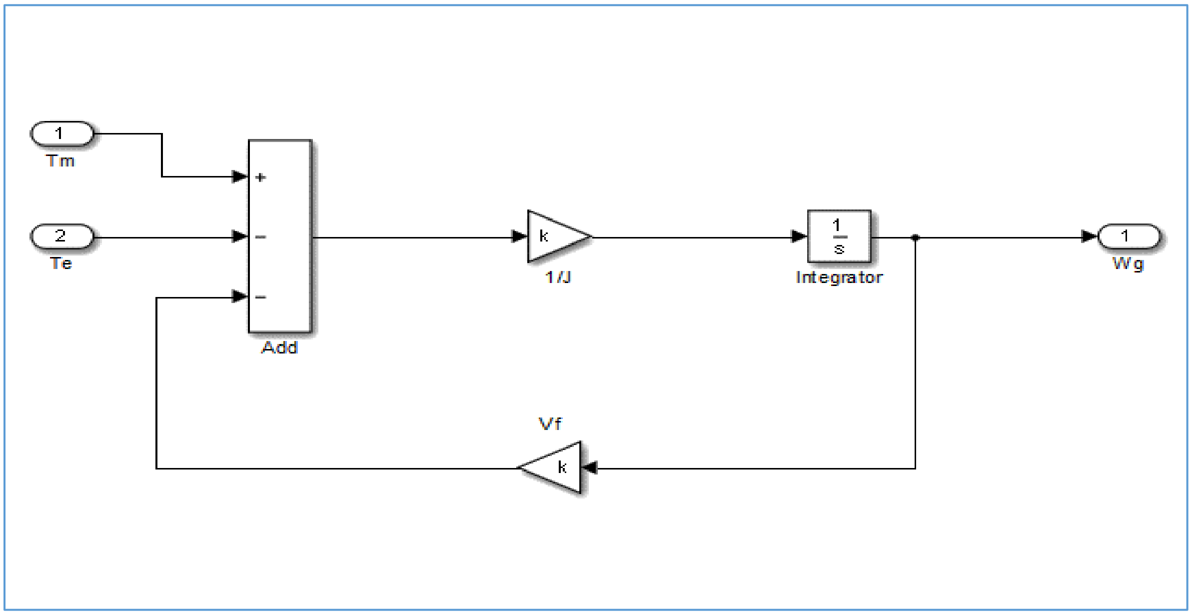


Figure 3.17 SIMULINK drive train and shaft model

The drive train system was considered as consisting of a number of discrete masses. Thus,

$$J\frac{dw_g}{dt} = T_m - T_e - V_f w_g \tag{3-41}$$

$$T_m = \frac{P_{act}}{w_r} = \frac{0.5\rho C_p(\lambda,\beta)AV^3}{w_r} \tag{3-42}$$

J, summation of rotor and generator inertia

T_m , turbine mechanical torque

T_e , generator electromagnetic torque

V_f , viscous friction coefficient or damping ratio

w_g , generator angular speed

3.5.5 Permanent Magnet Synchronous Generator (PMSG)

Clarke/Park transformation was applied due to least complexities in voltage equations [8] to simulate dynamic behavior of PMSG as shown in Figure 3.18, preferred over other types of generators because when used in water and wind energy systems, the simple structure's ability to operate at slow speed and self-excitation capability leads to a high power factor and high efficiency operation. PMSG low speed operation is the no need for a gearbox which often suffers from faults and requires regular maintenance making the system unreliable. The choice reduces the weight of the nacelle [9], [12], costs, losses and factors favorable for offshore applications. PMSG disadvantages are fixed excitation, high costs due to permanent magnet materials, and low speed effect on grid frequency network.

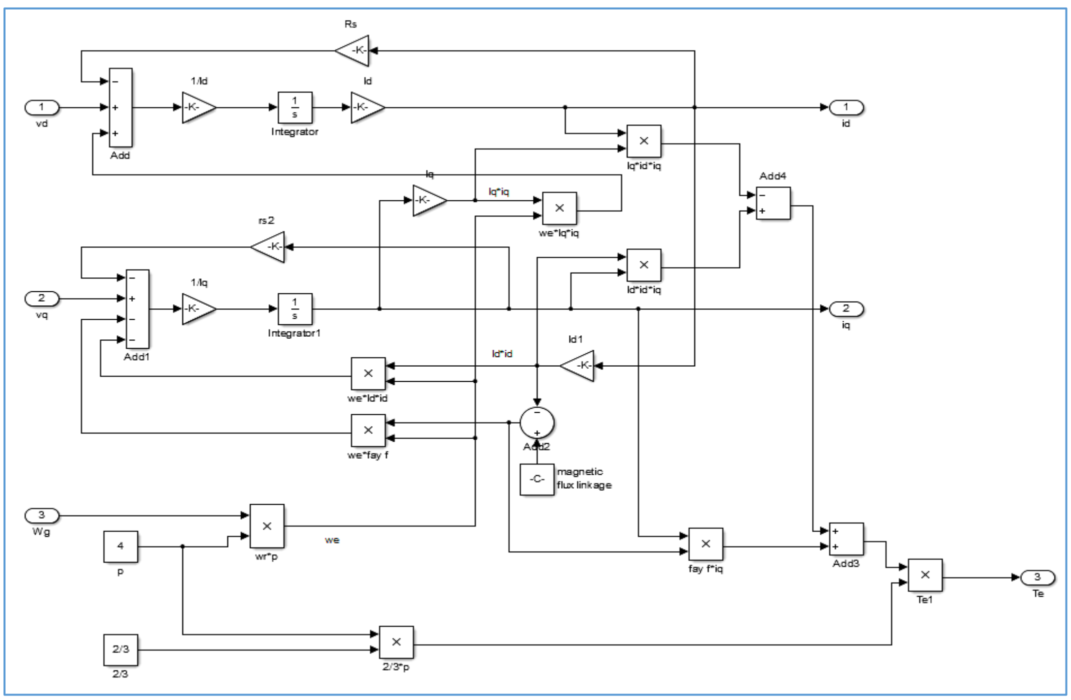


Figure 3.18 Simulink Model of a PMSG-based generation system

The PMSG mathematical model according to the synchronous d-q reference frame [3], [83], [84]

$$V_d = -L_q i_q \omega_e + L_d \frac{di_d}{dt} + Ri_d \tag{3.43}$$

$$V_q = L_d i_d \omega_e + L_q \frac{di_q}{dt} + Ri_q + \varphi_{pm} \omega_e \tag{3.44}$$

$$\varphi_d = L_d i_d + \varphi_{pm} \tag{3.45}$$

$$\varphi_q = L_q i_q \tag{3.46}$$

$$\omega_e = P\omega_g \tag{3.47}$$

V_d, V_q Direct and quadrature stator voltages respectively

L_d, L_q Direct and quadrature stator inductances respectively

R = resistance of the stator windings, P = Number of poles,

F=friction of rotor, and θ = rotor angular

i_d, i_q Direct and quadrature stator currents respectively

φ_d, φ_q Direct and quadrature stator fluxes respectively, φ_{pm} Permanent magnet flux

ω_e, ω_g Electrical (rotor) and generator (stator) angular velocity respectively

The electromagnetic torque, $T_e = \frac{3}{2}\{P(L_q - L_d)i_d i_q + \varphi_{pm} i_q\}$ (3.48)

The dynamic equations are given by:

$$\frac{d}{dt}\omega_e = \frac{1}{j}(T_e - F\omega_e - T_m) \tag{3.49}$$

$$\frac{d}{dt}\theta = \omega_e \tag{3.50}$$

3.6 Project analysis summary, Table 3-7

Table 3-7 PMSG Parameters [92]

Line Rated voltage	24 Volts
Rated power	1.5 MW at v = 2.5 m/s
Supply frequency	AC, 50 Hz-3φ
D-axis inductance	3.21mH
Q-axis inductance	0.971mH
Stator Leakage reactance	0.308 mH
Stator resistance	2.90 mΩ

3.7 Simulation preview exercise for tidal energy model

(a) Construction of hydrodynamic equations corresponding to tides and tidal currents' parameters mainly on fluid density and velocity.

(b) Design and development of a software model for computation of equivalent parameters' estimates for the electrical power generated outlined in Figure 3.19.

(c) Cost optimization with reference to environmental and economic feasibility impacts.

(d) Design and implementation of a hydrodynamic finite volume numerical model with an inclusion of an algorithm for computing electric power estimate from ocean tides and tidal current resources.

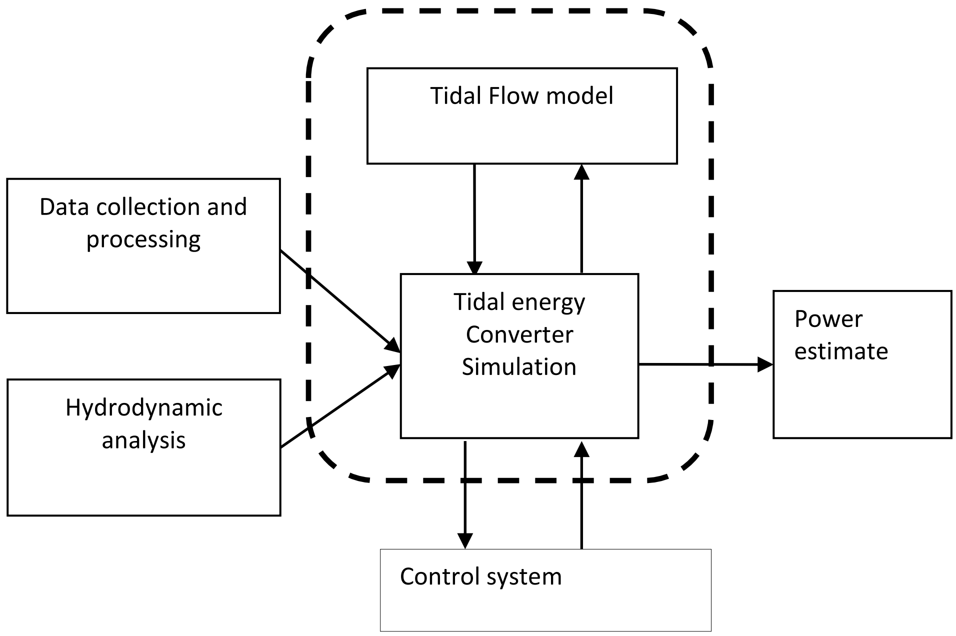
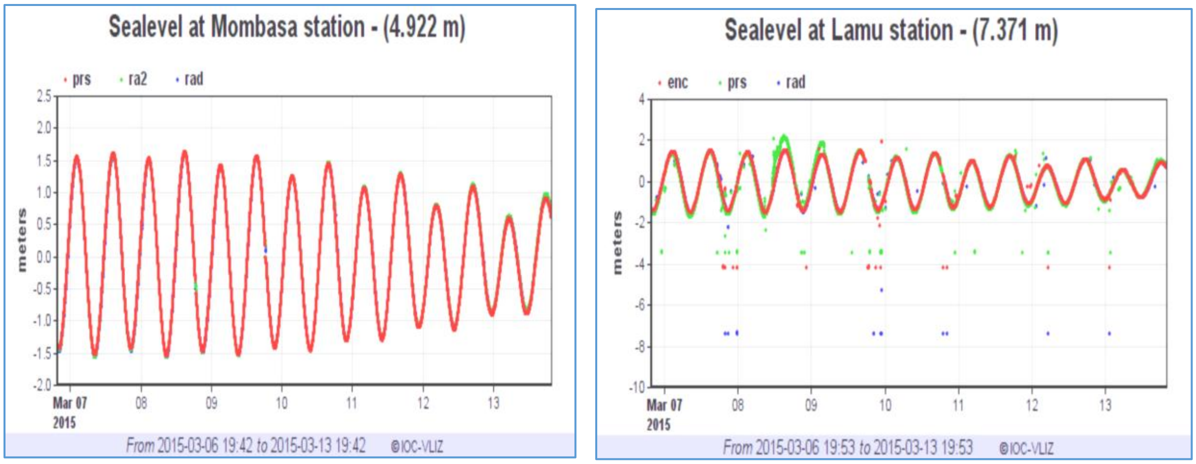


Figure 3.19 Methodology structure employed to access suitability of resource characteristic

3.7.1 Modelling and assessment of Tidal current Energy Resource along Kenyan coastline

A number of evaluation tools (CFD model, Excel and Matlab) were utilized to replicate and analyze the resource characteristics, modelling tidal flows and hydraulics for Mombasa and Lamu as shown in Figure 3.20.



(a) Mombasa (b) Lamu

Figure 3.20 Sea level at Mombasa and Lamu stations from 6/3/2015 to 13/3/2015 at 19:42

3.7.2 Business Model

Model for economic and finance scheme parameters of the tidal stream energy entailed:

(a) Technology costs from the device infrastructure included design, intellectual property, the manufacturing, sales and the marketing costs.

(b) Site-specific costs were diverse on installation, permissions and leases. Installation itself, power transformation, grid connection, site clearance and equipment disposal costs were considered.

(c) Annual costs account for routine, operation and maintenance of equipment. Unscheduled repairs, instrumentation, measurements as well as insurances and administrative costs.

(d) Cost of finance on the capital costs of the equipment, loans or equity investment, interest repayment and the premiums for the investors were incorporated.

(e) The income calculation was determined by the expected power output which is a combination of three techniques namely: long term current metering, computer modelling and tidal datum. The sale price is dependent on negotiation either with a utility, or a local user with available country subsidies.

3.7.3 Summary

The main aim of the thesis report was to evaluate the tidal stream resource potential for power extraction of an array of tidal energy conversion system, TECS. Numerous global research and development efforts show tidal energy can be a realistic renewable energy source, with majority of current tidal technologies presently being in the planning and development stage.

The analysis was based on hydrokinetic power generating system which depends on resource availability; thus must be identified by preliminary assessment and survey. In tidal generation, power quality problems are voltage variation and frequency changes due to dynamic load conditions. Therefore, grid integration and investigation of energy storage systems of the power output is a subject worth investigation on operation and reliability.

CHAPTER 4: TESTING MODELS AND ANALYSIS

4.1 Tidal Phenomena

Fluid flow characteristics were modeled and analyzed applying the following principles as summarized [27]:

4.1.1 Bernoulli's equation was applied with regard to conservation of energy (non-viscous, incompressible fluid, steady flow and frictionless) as summarized in Figure 4.1. This enabled the calculation of a frictional coefficient, velocity characteristic and flow rate, $Q = \mathrm{VA}$, be determined relative to frictional losses for the average steady energy extraction from different flow speeds, device geometry and roughness coefficient.

$$V_{(\text{theoretical})} = \left(\sqrt{(2g \times (\Delta h))} - E_{\text{friction}}\right) \tag{4-1}$$

Where g is acceleration gravity in m/s^{2,} Δh is change height in metres, m and E_{friction} is the frictional coefficient

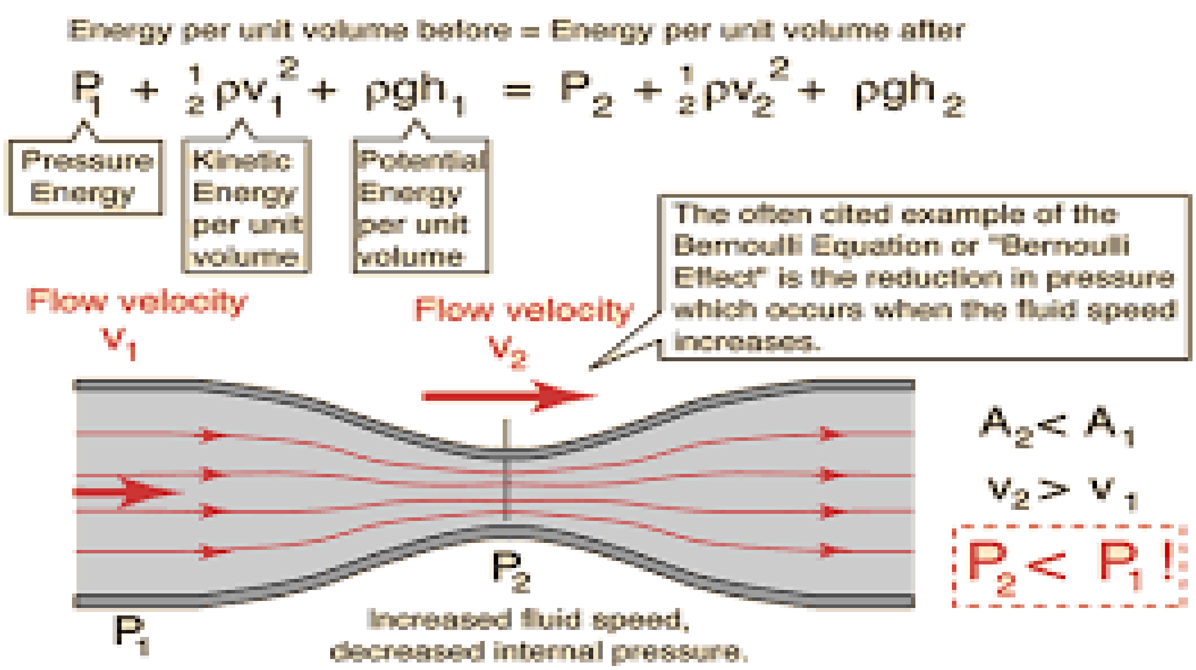
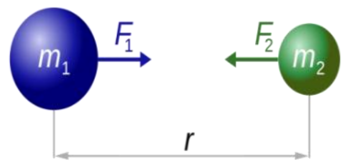


Figure 4.1 Bernoulli's equation

4.1.2 **Newton's Law** – law of conservation

The sun-moon system coupled with the earth's rotations slightly distorts the earth's gravitational pull to induce tide-generating forces. The circulation theorem is obtained by taking the line integral of Newton's second law for a closed chain of fluid particles.

The gravitational force exerted on the earth by the moon is calculated as shown in Figure 4.2.



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2} \tag{4-2}$$

Figure 4.2 Gravitational forces

4.1.3 **Chezy, Kutter, and Manning's equations** – gravity flow in open channels and roughness coefficients

In open channels the relationship of the hydraulic radius R, cross sectional area at inlet A, wetted perimeter W.P (distance from high to low water mark along the sea bed slope n) [89] is illustrated in Figure 4.3.

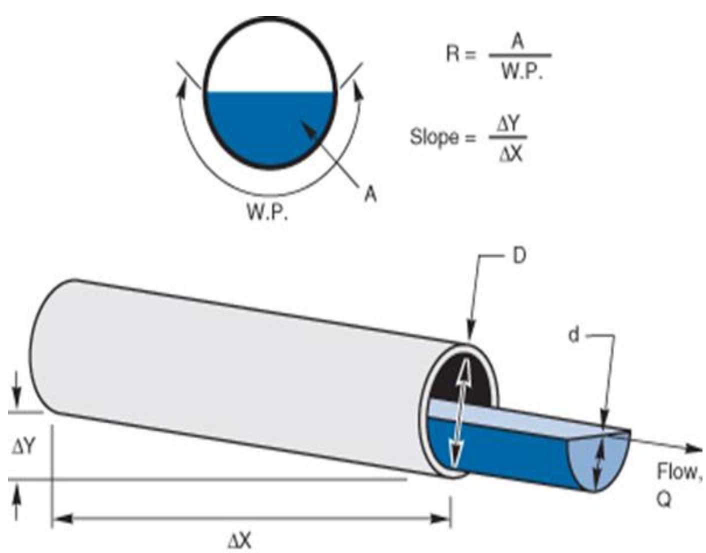


Figure 4.3 conditions for maximum flow velocity for a channel

The specific energy was equivalent to the sum of the depth of flow, discharge and the velocity head as shown in Figure 4.4. Using Manning's equation to the flow and accounting for roughness factors through various coefficients [27] [49] - [51]:

$$\text{Average flow Velocity, } V = \left(\frac{1}{n}\right) \times R^{\frac{2}{3}} \times S^{\frac{1}{2}}$$

(4-4)

S = H/L

H = head difference given by the phase difference, resolved as a gradient over the channel length

L = Channel length

(4-5)

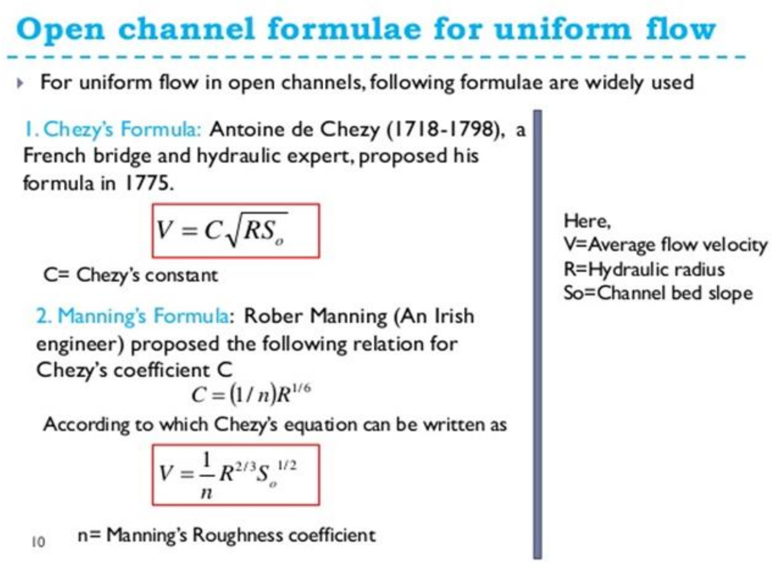


Figure 4.4 open channel flow analysis

4.1.4 Significant impact factor, (SIF)

The percentage of finite extractable power was modeled in terms of the blockage effects displayed as a proportion of flow through the device and their swept area, in the absence transforming the site's mainstream flow speed [81]. Subsequent sequential addition of turbines, adversely affect energy capture and varies the characteristics of the ocean resource. The SIF is unique to diverse sites and varies between 10% and 50% of the energy in the flow taking into consideration the tidal energy resource characteristics variation with the placement and quantification of the energy extraction devices, [81]. The average flow rate is exposed to a net decrease with localized increases contributing to turbulence with impact on the site topography from sediment transport, erosion and deposits.

4.2 Hydrodynamic forces

A net or differential tide-raising force, are based on the balance of orbital revolution on centrifugal and gravitational forces. The Excel spreadsheets presented in Table 4-1 to 4-10 illustrate a detailed 28-day cycle of spring and neap tides and finally an average tide for both Mombasa and Lamu sites. The averaging of data was and is critical to accommodate normalization for error limitation, and variability of tides and tidal current flow over the study period, [27], [28].

4.2.1 Tidal energy

The following are some of the astronomical forces exerted on the planet earth illustrated in Figure 4.5:

$$F_S = G\frac{m_E m_S}{r_S^2} \qquad \text{and} \qquad F_M = G\frac{m_E m_M}{r_M^2} \tag{4-6}$$

$$\frac{F_S}{F_M} = \frac{m_S}{m_M} \times \frac{r_M^2}{r_S^2} = \frac{26900000}{390^2} = 176 \tag{4-7}$$

Attraction due to the sun is 176 times more than the attraction due to the moon.

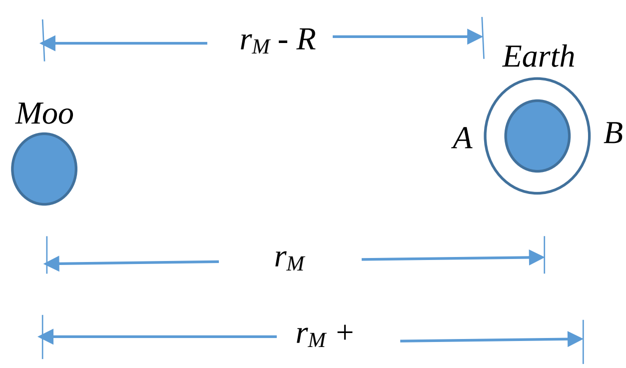


Figure 4.5 Differential gravitational forces

Differential force of attraction, $F = F_A - F_B = Gm_E\mu \frac{(r_M+R)^2-(r_M-R)^2}{(r_M-R)^2(r_M+R)^2}$

(4-8)

$$F = Gm_E\mu \frac{4R}{{r_M}^3\left(1-\frac{R^2}{{r_M}^2}\right)^2}$$

(4-9)

$$\frac{R}{r_M} = \frac{1}{60}$$

(4-10)

$$T_M = F_A - F_B = Gm_M\mu \frac{4R}{{r_M}^3}$$

(4-11)

$$T_S = F_A - F_B = Gm_S\mu \frac{4R}{{r_S}^3}$$

(4-12)

$$\frac{T_M}{T_S} = \frac{m_M}{m_S} \times \frac{{r_S}^3}{{r_M}^3} = \frac{390^3}{26800000} = 2.2$$

(4-13)

Differential attraction means tidal bulges (two-high and two-low) either towards the moon or the sun coupled with the earth's rotation effect. These create gravitational pull changes of tidal currents out of phase with each other with respect to time and location. Tidal constituents are the net result of the multiple influences impacting tidal changes over certain periods of time. An alternative is to treat the tidal flows as complex numbers, since each value has both magnitude and direction

4.3 Data Analysis

Manning's theory factors site parameters e.g. flow rate Q, area A, channel slope Δh, pressure P, mass m, gravity 'g', friction 'f ' and the equivalent velocity V, in the tidal profile analysis, Appendix B.

For calculation purposes extracts of the data used are given in Table 4-1 and equation (4-1). Data study was compared on two occasions 9th July to 7th October 2016.

4.4 Resource characteristic and Appropriate Technology

In a bid to explore marine tidal resources in Mombasa and Lamu, data categories from direct measurements and computational data analysis were vital in the assessment of the suitability of site.

Further examination on topography (bathymetry), flow velocity, channel dimensions, proximity to electric grid, orography and seabed roughness formed significant estimates in the data spreadsheets presented in Appendix B and Appendix C.

Technology design and deployment investigation considered horizontal axis turbines, which in general are better developed over vertical axis turbines, venturi based systems, and variable foil systems.

4.5 Power Calculations:

Application of data obtained as tabulated in Table 4-1 to Table 4-4, a variety of ocean parameters were analyzed. The tidal range of Mombasa is 4 m

The surface area of the tidal energy harnessing plant is (2000 m × 2000 m) = 4,000,000 m^2

Specific density of ocean water = 1025.18 kg/m^3

Mass of the water = (volume of ocean water) × (specific gravity of ocean water)

= (area × tidal range of water) × (mass density of water)

= (2000 x 2000 × 4) × (1025.18) [m] x [m] x [m] x [kg/m^3]

= 16.4×10^9 kg

(4-14)

Potential energy content of the water in the channel at high tide :

= (½ × area × density × gravitational acceleration × tidal range squared)

= (½ × 2000 × 2000 × 1025 kg/m^3 × 9.81 m/s^2 × $(4\ m)^2$

= 321.8×10^9 J

(4-15)

Total energy potential per day for a single high tide × 2

Everyday there is 2 high tides and 2 low tides.

= (high tide x 2) + (Low tide x2) [zero potential energy at low tide]

= $(321.8 \times 10^9 \times 2)$ J + (0 x 2) J

= 643.6×10^9 J

(4-16)

Mean power generation potential per day

= Energy generation potential / time in 1 day

= 643.6×10^9 J / 86400 s

= 7.45 MW

(4-17)

Assuming the power conversion efficiency to be 30%:

The daily-average power generated = 7.45 MW x 30%

= 2.23 MW

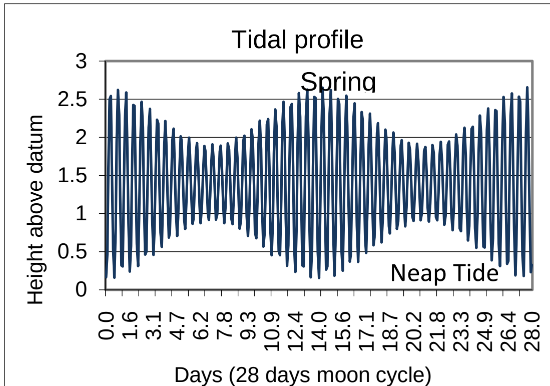
(4-18)

Table 4-1 Details of Test Site parameters

<table>
<tr><td colspan="3">Mombasa</td><td colspan="3" rowspan="12"></td><td colspan="3">Lamu</td><td colspan="2" rowspan="12"><u>NOTES</u>:
Mombasa and Lamu site values of channel dimensions (depth, distance, and CSA) of the proposed tidal energy equipment location. Main features of channel estimates applied on numerical models and excel spreadsheets, Table 4.2 to Table 4.4</td></tr>
<tr><td>Depth (m)</td><td>Distance (m)</td><td>CSA (m^2)</td><td>Depth (m)</td><td>Distance (m)</td><td>CSA (m^2)</td></tr>
<tr><td>4</td><td>28</td><td>112</td><td>57</td><td>133</td><td>7581</td></tr>
<tr><td>7</td><td>844</td><td>5908</td><td>34</td><td>80</td><td>2720</td></tr>
<tr><td>11</td><td>2195</td><td>24145</td><td>46</td><td>171</td><td>7866</td></tr>
<tr><td>17</td><td>118</td><td>2006</td><td>25</td><td>45</td><td>1125</td></tr>
<tr><td>22</td><td>64</td><td>1408</td><td>25</td><td>51</td><td>1275</td></tr>
<tr><td>16</td><td>124</td><td>1984</td><td>12</td><td>21</td><td>252</td></tr>
<tr><td>11</td><td>317</td><td>3487</td><td>7</td><td>12.5</td><td>87.5</td></tr>
<tr><td>5</td><td>623</td><td>3115</td><td>11</td><td>69</td><td>759</td></tr>
<tr><td>1</td><td>257</td><td>257</td><td>8</td><td>153</td><td>1224</td></tr>
<tr><td></td><td></td><td>42422</td><td colspan="2"></td><td>22889.5</td></tr>
<tr><td>Average Depth</td><td>Total distance</td><td>Average Cross Sectional Area (CSA)</td><td>Difference</td><td>Mean (CSA)</td><td rowspan="2"></td><td>Average Depth</td><td>Total distance</td><td>Average Cross Sectional Area (CSA)</td><td>Difference</td><td>Mean (CSA)</td></tr>
<tr><td>9.4</td><td>4570</td><td>42958</td><td>-536</td><td>42690</td><td>25</td><td>735.5</td><td>18387.5</td><td>4502</td><td>20638.5</td></tr>
</table>

Table 4-2a Measured tidal profile parameters of Mombasa (Kilindini Port)

Kilindini Port Data: Obtained from Kilindini Tidal station. Marine Tidal Gauge equipment installed by University of Hawaii Sea Level Centre (UHSLC) is SLPR2. SLPR2 collects and transmit data at an interval of 28 minutes via the Global Positioning System, (GPS).				**Date:**	**1st - 28th**	**July**	**2015**
Height above chart datum (default 1.5m):			2.2	days/ degree:	hrs/deg:	mins/deg:	sec/deg
Period of interest in days (frequency) :			28	0.078	1.867	112	6720
Maximum tidal range for period:			4				
Minimum tidal range for period:			0.1		trim for..	amplitude	
Days	Seconds	Degrees	Radians	Sin function (Tide height)	Decay	Regrowth	Exp factor
0	0	0	0	0.262	2.95		1
1.01	87360	13	0.227	0.510	2.874		1
2.02	174720	26	0.454	0.946	2.662		1
3.03	262080	39	0.681	1.456	2.356		1
5.06	436800	65	1.134	2.299	1.718		1
6.07	524160	78	1.361	2.571	1.515		1
7.00	604800	90	1.571	3.176	1.450		1
9.02	779520	116	2.025	3.162	1.738		-1
10.03	866880	129	2.251	3.063	2.044		-1
11.04	954240	142	2.478	2.811	2.381		-1
12.06	1041600	155	2.705	2.388	2.682		-1
14.00	1209600	180	3.142	0.238	2.950		-1
18.04	1559040	232	4.049	1.454	2.019		1
19.06	1646400	245	4.276	1.865	1.718		1
19.99	1727040	257	4.485	3.028	1.526		1
21.00	1814400	270	4.712	3.118	1.450		1
22.01	1901760	283	4.939	3.226	1.526		-1
23.02	1989120	296	5.166	3.341	1.738		-1
25.04	2163840	322	5.620	3.317	2.381		-1
28	2419200	360	6.283	0.493	2.950		-1



Spring and Neep Tides occur twice a

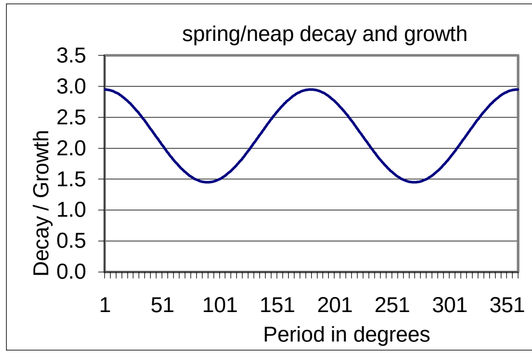
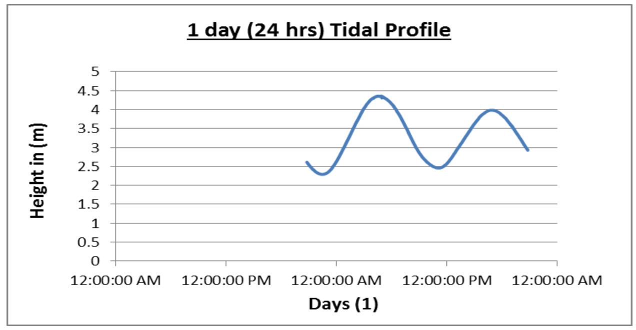
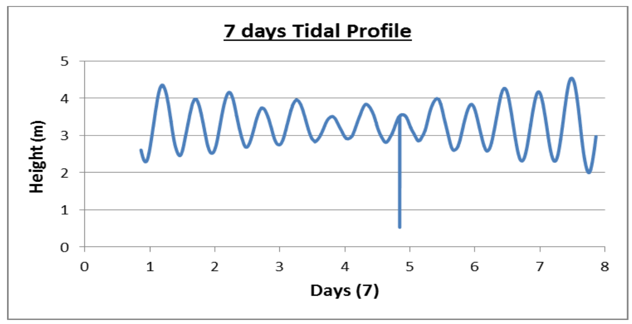


Table 4-2b Tide profile at Mombasa

Tide Profile at Mombasa		
Time (UTC)	**Time**	**prs(m)**
9/7/2016 20:45	20:45	2.613
9/7/2016 20:46	20:46	2.605
9/7/2016 20:47	20:47	2.602
9/7/2016 20:48	20:48	2.596
9/7/2016 20:49	20:49	2.591
9/7/2016 20:50	20:50	2.584
9/7/2016 20:51	20:51	2.579
9/7/2016 20:52	20:52	2.574
9/7/2016 20:53	20:53	2.567
9/7/2016 20:54	20:54	2.562
9/7/2016 20:55	20:55	2.559
9/7/2016 20:56	20:56	2.554
9/7/2016 20:57	20:57	2.543
9/7/2016 20:58	20:58	2.54
9/7/2016 20:59	20:59	2.538
9/7/2016 21:00	21:00	2.527
9/7/2016 21:01	21:01	2.527
9/7/2016 21:02	21:02	2.522
9/7/2016 21:03	21:03	2.514
9/7/2016 21:04	21:04	2.507
9/7/2016 21:05	21:05	2.506
9/7/2016 21:06	21:06	2.502
9/7/2016 21:07	21:07	2.497
9/7/2016 21:08	21:08	2.49
9/7/2016 21:09	21:09	2.489
9/7/2016 21:10	21:10	2.484
9/7/2016 21:16	21:16	2.457
Data up to 1 day (24 Hours)		
9/8/2016 20:46	20:46	2.926
Data up to 7 days		
9/14/2016 20:45	8:44:00	2.972
9/14/2016 20:46	8:45:00	2.978
Data up to 30 days		
9/7/2016 21:30	21:30	2.404
10/7/2016	20:30	2.803





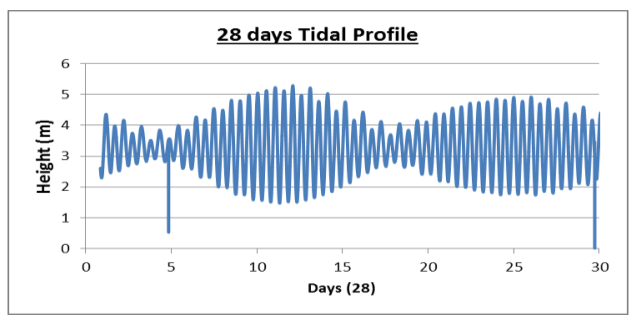


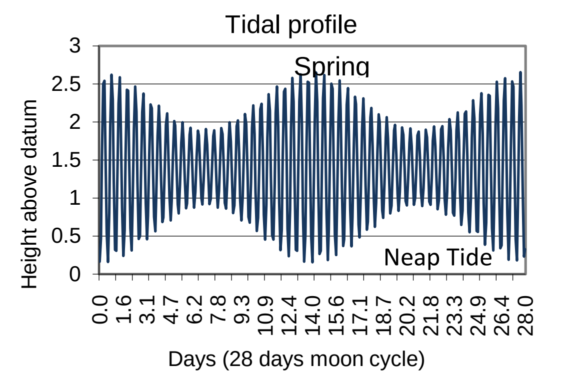
Table 4-3a Measured Parameters of Lamu Port

Lamu Port Data: Obtained from Lamu Tidal station. Marine Tidal Gauge equipment installed by University of Hawaii Sea Level Centre (UHSLC) is SLPR2. SLPR2 collects and transmit data at an interval of 28 minutes via the Global Positioning System (GPS).		**Date:**	**1st - 28th**	**July**	**2015**
		Time step interval			
height above chart datum (default 1.5m):	1.4	days/degree:	hrs/deg	mins/deg	sec/deg
Peroid of interest in days (frequency) :	28	0.07778	1.86667	112	6720
Maximum tidal range for period:	2.3				
Minimum tidal range for period:	0.1		trim for..	amplitude	
		0.65	2	0.6	

Period const
tides/week
13.530201
1.9328859

tidal range reduction per week	2.2
amplitude factor	n/a

days	seconds	degrees	radians	sin function (tide height)	Decay	Regrowth	exp factor
0.0	0	0	0	0.16195	2		1
1.0	87360	13	0.227	0.318	1.939		1
2.0	174720	26	0.454	0.602	1.769		1
3.0	255360	38	0.663	1.812	1.545		1
4.0	342720	51	0.890	1.933	1.275		1
5.0	430080	64	1.117	1.951	1.031		1
6.0	517440	77	1.344	1.923	0.861		1
7.0	604800	90	1.571	1.905	0.800		1
8.0	692160	103	1.798	1.920	0.861		-1
9.0	779520	116	2.025	1.943	1.031		-1
10.0	866880	129	2.251	1.918	1.275		-1
12.0	1034880	154	2.688	0.583	1.769		-1
14.0	1209600	180	3.142	0.156	2.000		-1
15.0	1296960	193	3.368	0.182	1.939		1
16.0	1384320	206	3.595	0.368	1.769		1
17.0	1464960	218	3.805	1.455	1.545		1
18.0	1552320	231	4.032	1.671	1.275		1
19.0	1639680	244	4.259	1.784	1.031		1
20.0	1727040	257	4.485	1.832	0.861		1
21.0	1814400	270	4.712	1.872	0.800		1
22.0	1901760	283	4.939	1.942	0.861		-1
23.0	1989120	296	5.166	2.037	1.031		-1
24.0	2069760	308	5.376	1.505	1.255		-1
26.0	2244480	334	5.829	0.924	1.769		-1
27.0	2331840	347	6.056	0.586	1.939		-1
28.0	2419200	360	6.283	0.327	2.000		-1



Spring and Neep Tides occur twice a

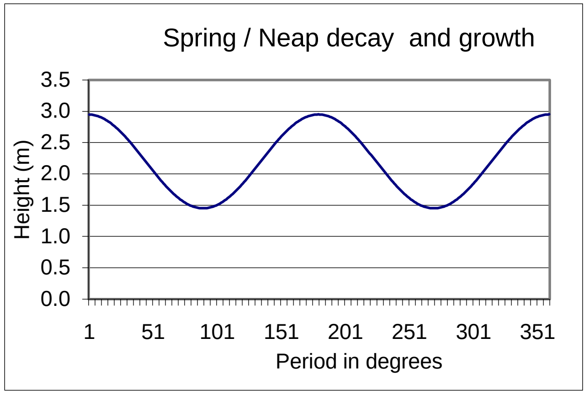
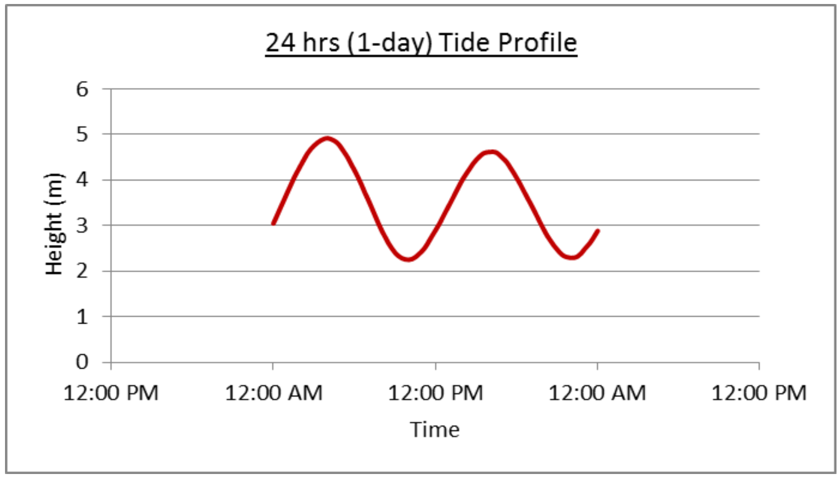
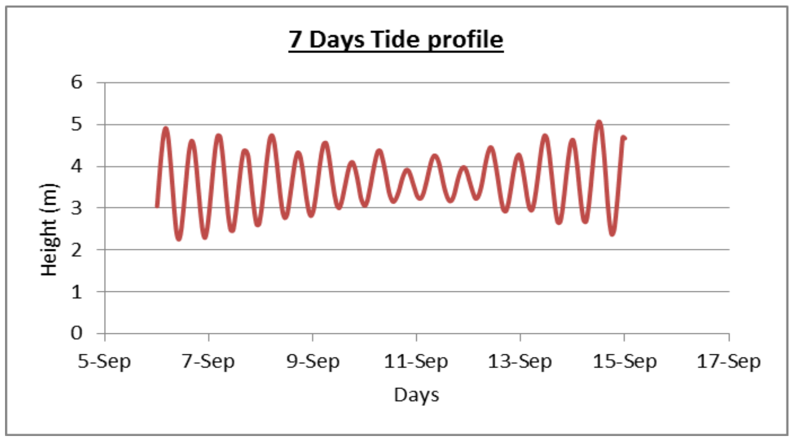


Table 4-3b Tide profile at Lamu

Tide gauge at Lamu		
Time (UTC)		prs(m)
9/6/2016 0:00		3.045
9/6/2016 1:00		3.706
9/6/2016 2:00		4.311
9/6/2016 3:00		4.755
9/6/2016 4:00		4.917
9/6/2016 5:00		4.717
9/6/2016 6:00		4.217
9/6/2016 7:00		3.573
9/6/2016 8:00		2.901
9/6/2016 9:00		2.405
9/6/2016 10:00		2.25
9/6/2016 11:00		2.438
9/6/2016 12:00		2.894
9/6/2016 13:00		3.447
9/6/2016 14:00		4.012
9/6/2016 16:00		4.616
9/6/2016 17:00		4.473
9/6/2016 18:00		4.047
9/6/2016 19:00		3.493
9/6/2016 21:00		2.473
9/6/2016 22:00		2.29
9/6/2016 23:00		2.466
9/7/2016 0:00		2.884
9/7/2016 1:00		3.429
9/7/2016 2:00		3.997
9/7/2016 3:00		4.468
9/7/2016 4:00		4.734
9/7/2016 5:00		4.719
9/7/2016 6:00		4.386
9/7/2016 7:00		3.847
9/7/2016 8:00		3.264
9/7/2016 9:00		2.768
9/7/2016 10:00		2.48
9/7/2016 11:00		2.463
9/7/2016 12:00		2.76
9/7/2016 13:00		3.19
9/7/2016 14:00		3.674
9/7/2016 15:00		4.094
9/7/2016 16:00		4.366
9/7/2016 17:00		4.375
9/7/2016 18:00		4.256
9/7/2016 19:00		3.82
9/7/2016 20:00		3.319
9/7/2016 21:00		2.885
9/7/2016 22:00		2.607
9/7/2016 23:00		2.613
9/8/2016 0:00		2.902
9/8/2016 1:00		3.328
9/8/2016 2:00		3.822
9/8/2016 3:00		4.29
9/8/2016 4:00		4.641
9/8/2016 5:00		4.749
9/8/2016 6:00		4.588
9/8/2016 7:00		4.208
9/8/2016 8:00		3.728
9/8/2016 9:00		3.252
9/8/2016 10:00		2.907
9/8/2016 11:00		2.763
9/8/2016 12:00		2.849





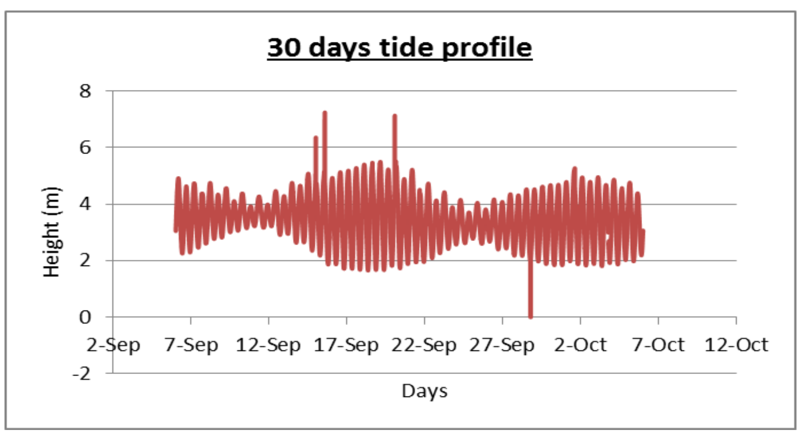


Table 4-4a Phase difference between Mombasa Port and Lamu port

Phase difference between Kilindini and Lamu, characteristic flow parameters gleaned.							
			degrees	radians	Am		
Mombasa phase angle:			-102.75	-1.7933	2.2		
Lamu phase angle:			-101.571	-1.7728	1.4		
				spring			
sin (MSA	sin LAMU	1st-2nd	Days	Min	Max	tidal range	
0.262	0.162	0.101	0.000	0.0818	1.5156	1.4338546	Na
0.510	0.318	0.192	1.011				Na
0.946	0.602	0.344	2.022				Na
1.456	0.931	0.525	3.033				Na
1.928	1.226	0.703	4.044				Na
2.299	1.442	0.857	5.056				Na
2.571	1.585	0.986	6.067				Na
3.176	1.920	1.256	8.011				1.256
3.162	1.943	1.219	9.022				1.219
3.063	1.918	1.145	10.033				1.145
2.811	1.791	1.021	11.044				1.021
2.388	1.541	0.848	12.056				0.848
1.847	1.202	0.646	13.067				0.646
0.238	0.156	0.082	14.000				0.082
0.281	0.182	0.099	15.011				0.099
0.561	0.368	0.192	16.022				0.192
0.990	0.652	0.337	17.033				0.337
1.454	0.951	0.503	18.044				0.503
1.865	1.202	0.663	19.056				0.663
3.226	1.942	1.284	22.011				1.284
3.341	2.037	1.303	23.022				1.303
3.399	2.110	1.289	24.033				1.289
3.317	2.094	1.223	25.044				1.223
3.040	1.945	1.095	26.056				1.095
2.580	1.666	0.915	27.067				0.915
0.493	0.327	0.165	28.000				0.165

Form of function => a(t) = Am cos (ωt+Φ)			
Phasor form => Am ∟Φ			
Width at opening	4666	width at exit Lamu	770

Neap		
Min	Max	tidal range
1.5156202	0.0817656	1.4338546

Mombasa - Kilindini				
Depth	Distance	CSA		
1	57	57		
4	28	112		
7	844	5908		
17	118	2006		
22	64	1408		
16	124	1984		
11	317	3487		
5	623	3115		
1	257	257		
		42479		
av. depth	total dist.	av. CSA	Difference	Mean CSA

Lamu				
depth	distance	CSA (msq)		
57	133	7581		
25	45	1125		
25	51	1275		
12	21	252		
7	12.5	87.5		
11	69	759		
8	153	1224		
		22889.5		
average depth	Total distance	Avg. CSA	Difference	Mean CSA
25	735.5	18387.5	4502	20638.5
Distance between sites: nm				
	5.36			
	meters:			
	1852	5.36	9926.72	
	gradient of bed	0.0015506(S)		

4.6 Phase Resultant

Mombasa and Lamu tidal height data were entered in the excel spreadsheets, which calculated the resultant phase difference as shown in Table 4.2 to 4.4, such that one site would lag or lead the other during flood and ebb tides depending on the position on the earth [53]. The channels cross-sectional areas and Manning's coefficients on seabed roughness fed in the excel tool calculates the average bulk flow (tidal velocity) [50]. The resultant phase graph, Table 4.4 shows the magnitude and the effective polarity of the head difference at the sites which yield the energy gradient using the Manning's theory, gravity head in Bernoulli's principle. The values, unit dimensions and parameters were analyzed manually, though CAD could facilitate the application using vector software and profile mapping [51].

Data analysis in Table 4.4a and Table 4.4b were applied to determine the phase resultant between Mombasa and Lamu and demonstrate the characteristic flow [27].

Table 4-4b Flow rate parameters for Mombasa and Lamu

Form function, $at = A_m \cos(\omega t + \phi)$, $\phi\ (\lambda, \beta)$, where Phasor form $A_m = L\phi$	
Width at Mombasa opening	466 m
Width at Lamu exit	770 m
Cross Sectional area at Mombasa Kilindini channel entrance	42479 m^2
Cross Sectional area at Lamu channel entrance	22889.5 m^2
Average cross sectional area for both Mombasa and Lamu	32684 m^2
Wetted perimeter at Mombasa	4627 m
Wetted perimeter at Lamu	735.5 m
Average wetted perimeter	2681.25 m
Max tidal height difference	1.434 m
Minimum tidal height difference	1.434 m
Average tidal difference	1.434 m
Maximum spring tide	5.304 m/s = 10.310 knots
Maximum Neap tide	5.304 m/s = 10.310 knots
Average tide = 5.304 m/s = 10.310 knots	5.304 m/s = 10.310 knots
Frictional correction factor	0.3203 m/s

Therefore, for maximum spring and minimum neap tides of 1.698699 equivalent to 3.302 knots leading to an average tide of 1.698699 equivalent to 3.302 knots an average velocity of 2.05211 m/s is obtained.

4.6.1 Employed data

Site distance = 9926 m, Maximum and minimum slope = 0.000144454 m

Hydrochloric maximum = 9.18067, minimum = 31.121

For a 5-volt equipment, $V_{rms} = \frac{V_{Max}}{\sqrt{2}} = 2.8868\ V$, gravity = (9.81 m)⁄s^2 ,

(4-19)

4.6.2 Factors that determine the value of n for a channel

The selection of the Manning's roughness coefficient correction factor is based on the channels composition [64], [81] illustrated in Table 4-5 Appendix (C) and Appendix (D). Referenced were important factors affecting selection of channel n values in Appendix (D).

Table 4-5 Selection of channel n values

Interpolation of Manning solution for outlet:		4.403	2.265			Max neap
	Max spring	4.403	2.265		4.402675	2.26493158
		A_1V_1	A_2V_2	ΔE	loss/m	ratio loss
Venturi effect possible in channel $\rho A_1V_1 = \rho A_2V_2 - E_{fr}$		119971316	117537583	2433733.250	245.188	0.980

4.7 Generic models demonstrated, tested, assessed & analyzed, Tables 4-6 & 4-7

4.7.1 Significant Impact Factor, Rejuvenation and power calculations

Table 4-6a Generic Models

Variables			Over tidal cycle in question		
Omega, Ω	0.000140563 radians/s		Velocity, max spring		2.264932 m/s
Period, T	44700 seconds		Velocity, max neap		2.264932 m/s
Density	1027 kg / m^2		Velocity, average		2.264932 m/s
CSA	32684.25 m^2	Venturi CSA at deployment site			22889.5 m^2
Length	9926 m^2				
Volume	324423865.5 m^3	N value	0.031022		
Mass	3.33183E+11 kg				
Cut in	0.75 m/s				
Rated	2 m/s		Betz/GGS/Cp	0.44	

Table 4-6b Generic Models Continuation

Significant impact factor and thus, increased n for obstructions					n (obstruction)		Representative no.turbines, and likely no.			
Manning's	0.034354031	Obstruction coefficient for small % blockage			0.00333		10	3.6429771	2	500kW/tur
Manning's	0.037686362	Obstruction coefficient for med % blockage			0.00666		R = 10m	7.2859541	4	500kW/tur
Manning's	0.044936634	Obstruction coefficient for large % blockage			0.013905		R = 10m	10.928931	8	500kW/tur
	Reduction in average velocity due to increased n						Turbine rated power in kW, estimated			
Max	1.53392541	Max	1.3982915	Max	1.172685	m/s	Axial	X flow	Oschydr	Shrouded
Min	1.53392541	Min	1.3982915	Min	1.172685	m/s	500	500	500	750
Average	1.53392541	Average	1.3982915	Average	1.172685	m/s				
V loss	9.699970871	V loss	17.684546	V loss	30.96568	%				

Table 4-6c Velocity Calculation

Time, t		**Calculation steps**		**Velocity, V, max, min, and aver.**		
hours	seconds	Ωt	SIN Ωt	V SIN Ωt (1)	V SIN Ωt (2)	V SIN Ωt (3)
0	0	0	0	0	0	0
0.25	900	0.126507	0.12617	0.285766	0.285766	0.285766
0.5	1800	0.253014	0.250323	0.566965	0.566965	0.566965
1	3600	0.506028	0.484707	1.097829	1.097829	1.097829
2	7200	1.012057	0.847924	1.92049	1.92049	1.92049
3	10800	1.518085	0.998611	2.261786	2.261786	2.261786
4	14400	2.024113	0.898999	2.036172	2.036172	2.036172
5	18000	2.530142	0.574056	1.300198	1.300198	1.300198
6	21600	3.03617	0.105227	0.238333	0.238333	0.238333
7	25200	3.542198	-0.389976	-0.883269	-0.883269	-0.883269
8	28800	4.048227	-0.787433	-1.783483	-1.783483	-1.783483
9	32400	4.554255	-0.987523	-2.236672	-2.236672	-2.236672
10	36000	5.060283	-0.940093	-2.129245	-2.129245	-2.129245
11	39600	5.566312	-0.657031	-1.48813	-1.48813	-1.48813
12	43200	6.07234	-0.209286	-0.474019	-0.474019	-0.474019

Table 4-7 Power calculations tabulated

Time, t	Calculation steps		Velocity, V, max, min, and aver.			Power, W	Accel, a	Force, F	velocity
hours	Ωt	SIN Ωt	V SIN Ωt (1	V SIN Ωt (2)	V SIN Ωt (3)	0.5ρAV^3	V/t, m/s/s	Ma, N	m/s
0	0	0	0	0	0	0	0.00000	0	0
0.08	0.04216903	0.042156532	0.095777277	0.07740591	0.087077442	11081.434	0.00029	96709167	0.058973216
0.25	0.12650709	0.126169919	0.28665098	0.231667474	0.260613318	297076.835	0.00087	289440026	0.176500427
0.5	0.25301417	0.250323301	0.568720501	0.459632274	0.517061329	2320091.675	0.00172	574254017	0.350179898
0.75	0.37952126	0.370475838	0.841700327	0.680250904	0.765245298	7521093.396	0.00255	849889871	0.518262546
1	0.50602835	0.484707167	1.1012275	0.889997282	1.001198574	16843783.041	0.00334	1111942182	0.678061953
1.5	0.75904252	0.688227114	1.563613405	1.263691362	1.421584105	48216607.320	0.00474	1578826992	0.962768146
2	1.01205669	0.847923927	1.926435609	1.556919397	1.751449709	90172058.913	0.00584	1945179370	1.186169698
2.5	1.26507087	0.953628851	2.166591267	1.751009976	1.969791062	128274242.608	0.00657	2187671686	1.334041427
3	1.51808504	0.998611082	2.268788373	1.833604305	2.062705193	147295831.880	0.00688	2290863145	1.396967543
4	2.02411339	0.898999344	2.042476091	1.650701757	1.856949767	107468067.297	0.00619	2062348899	1.257619635
5	2.53014173	0.5740561	1.304223264	1.054055733	1.185755415	27981070.246	0.00395	1316913046	0.803053114
6	3.03617008	0.105227404	0.239070761	0.19321378	0.217355002	172340.714	0.00072	241396863	0.147203723
6.5	3.28918425	-0.147056346	-0.334103771	-0.270018183	-0.303755781	-470384.094	-0.00101	-337354522	-0.205718669
7	3.54219843	-0.389976226	-0.886004115	-0.716056631	-0.805524795	-8772345.151	-0.00269	-894624725	-0.545541843
7.5	3.7952126	-0.608064216	-1.381487797	-1.116499891	-1.2560017	-33254441.129	-0.00419	-1394929346	-0.850627426
8	4.04822678	-0.787433478	-1.7890047	-1.445849581	-1.626502202	-72217581.235	-0.00542	-1806411291	-1.101548972
8.5	4.30124095	-0.916662602	-2.082606023	-1.683134229	-1.893434536	-113927837.637	-0.00631	-2102869286	-1.282328953
9	4.55425512	-0.987522875	-2.243596588	-1.813244642	-2.039801679	-142443555.863	-0.00680	-2265426250	-1.381456133
9.5	4.8072693	-0.995502239	-2.261725255	-1.827895988	-2.056283647	-145924440.501	-0.00685	-2283731305	-1.392618549
10	5.06028347	-0.940092605	-2.135837676	-1.726155337	-1.941830943	-122889060.427	-0.00647	-2156618870	-1.315105431
10.5	5.31329764	-0.824822205	-1.873949792	-1.514501064	-1.703731389	-83000812.990	-0.00568	-1892182878	-1.153852456
11	5.56631182	-0.657030926	-1.492737416	-1.206410339	-1.357146068	-41952587.304	-0.00452	-1507261396	-0.919127471
11.5	5.81932599	-0.447402944	-1.016474397	-0.821500961	-0.924143936	-13246398.794	-0.00308	-1026364451	-0.625876682
12	6.07234016	-0.209286403	-0.47548697	-0.384282186	-0.432296574	-1355889.676	-0.00144	-480113345	-0.292772949
12.5	6.32535434	0.042156532	0.095777277	0.07740591	0.087077442	11081.434	0.00029	96709167	0.058973216

Table 4-7 Power calculations tabulated continuation

Time, t		Calculation steps		Velocity, V max, min, and aver.	velocity	Power, W	Ek/v loss	V after	rejuvenation	velocity	Power, W	Ek/v loss	V after	rejuvenation
hours	seconds	Ωt	SIN Ωt	V SIN Ωt (1)		$0.5\rho AV^3$	After turb.	m/s	m		$0.5\rho AV^3$	After turb.	m/s	m
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0833	300	0.04216903	0.042156532	0.095777277	0.054	2607.497366	0	0.054	1	0.045	1538.065818	0	0.045	1
0.5	1800	0.25301417	0.250323301	0.568720501	0.319	545925.1102	0	0.319	0	0.268	322020.9393	0	0.268	0
1	3600	0.50602835	0.484707167	1.1012275	0.618	3963396.882	0	0.618	0	0.518	2337860.566	0	0.518	0
1.5	5400	0.75904252	0.688227114	1.563613405	0.878	11345524.38	518191.232	0.864	108	0.736	6692303.302	458492.633	0.719	164
2	7200	1.01205669	0.847923927	1.926435609	1.081	21217778.47	969092.869	1.065	185	0.907	12515579.2	857447.817	0.886	281
2.5	9000	1.26507087	0.953628851	2.166591267	1.216	30183346.1	1378582.85	1.197	379	1.020	17804034.44	1219762.2	0.996	578
3	10800	1.51808504	0.998611082	2.268788373	1.273	34659187.87	1583010.77	1.254	3528	1.068	20444167.2	1400638.86	1.043	5378
4	14400	2.02411339	0.898999344	2.042476091	1.146	25287585.45	1154975.71	1.129	220	0.961	14916207.12	1021915.89	0.939	336
5	18000	2.53014173	0.5740561	1.304223264	0.732	6584036.752	300716.829	0.721	78	0.614	3883678.658	0	0.614	0
6	21600	3.03617008	0.105227404	0.239070761	0.134	40552.33005	0	0.134	0	0.113	23920.31282	0	0.113	0
7	25200	3.54219843	-0.389976226	-0.886004115	-0.497	-2064161.319	0	-0.497	0	-0.417	-1217572.071	0	-0.417	0
7.5	27000	3.7952126	-0.608064216	-1.381487797	-0.775	-7824878.056	-357390.55	-0.763	87	-0.650	-4615604.841	0	-0.650	0
8	28800	4.04822678	-0.787433478	-1.7890047	-1.004	-16993031.53	-776133.36	-0.989	146	-0.842	-10023557.94	-686718.35	-0.822	223
8.5	30600	4.30124095	-0.916662602	-2.082606023	-1.169	-26807590.4	-1224399.8	-1.151	269	-0.980	-15812801.57	-1083342	-0.957	410
9	32400	4.55425512	-0.987522875	-2.243596588	-1.259	-33517431.56	-1530862.6	-1.240	807	-1.056	-19770687.57	-1354498.5	-1.031	1231
9.5	34200	4.8072693	-0.995502239	-2.261725255	-1.269	-34336495.02	-1568272.2	-1.250	962	-1.065	-20253822.68	-1387598.3	-1.040	1466
10	36000	5.06028347	-0.940092605	-2.135837676	-1.199	-28916195.24	-1320707.5	-1.180	292	-1.005	-17056589.22	-1168554.4	-0.982	444
10.5	37800	5.31329764	-0.824822205	-1.873949792	-1.052	-19530361	-892022.4	-1.036	159	-0.882	-11520234.33	-789256.3	-0.861	242
11	39600	5.56631182	-0.657030926	-1.492737416	-0.838	-9871580.115	-450870.85	-0.825	96	-0.703	-5822878.343	-398927.95	-0.686	146
11.5	41400	5.81932599	-0.447402944	-1.016474397	-0.571	-3116920.68	0	-0.571	0	-0.478	-1838555.703	0	-0.478	0
12	43200	6.07234016	-0.209286403	-0.47548697	-0.267	-319045.2468	0	-0.267	0	-0.224	-188192.9373	0	-0.224	0
12.5	45000	6.32535434	0.042156532	0.095777277	0.054	2607.497366	0	0.054	0	0.045	1538.065818	0	0.045	1

4.7.2. Quantification of exploitable tidal energy resources

The turbine to turbine interaction was crucial to understand how energy shadowing an array of devices influences energy extraction by the individual devices as illustrated in Figure 4.6.

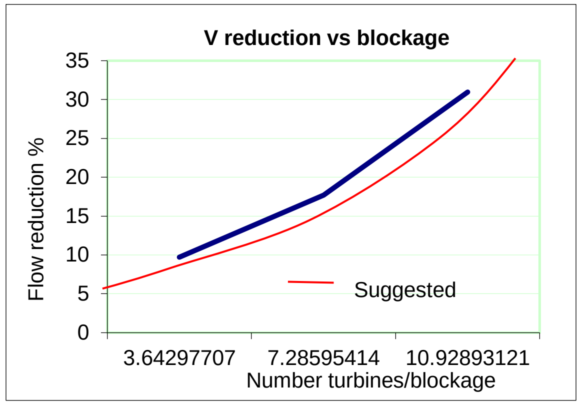


Figure 4.6 Wake interactions of turbines in a tidal stream farm

The shear velocity profile applicable in fluid dynamics as expressed in equation 4-12:

$$V_Z = V_1 \left(\frac{Z}{Z_1}\right)^{1/7} \tag{4-12}$$

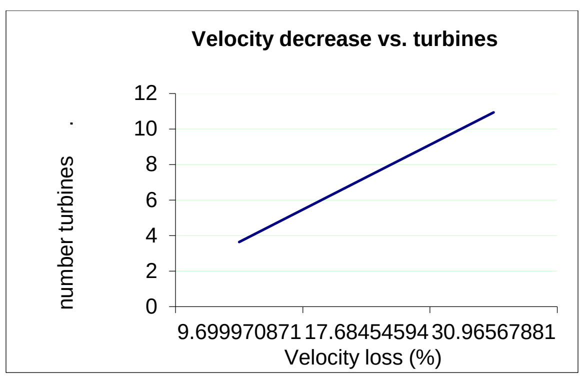


Figure 4.7 Velocity versus Number of turbines

The energy extracted in a tidal stream farm inevitably depends upon the inflow conditions to each device. Computational fluid dynamics, CFD and analytical techniques have to be employed to investigate wake interactions of turbines taking into account the fundamental differences in the working environments between the two technologies.

4.7.3 Energy and Environment interactions

Limitation on the upper bound amount of power generated depends on the number and size of turbines evident as shown in Figure 4.8 in which an increase of turbines block the flow in tidal channel. An isolated turbine is more effective than in an unbounded flow creating non-uniform downstream flow between the wake of the turbines and the free stream.

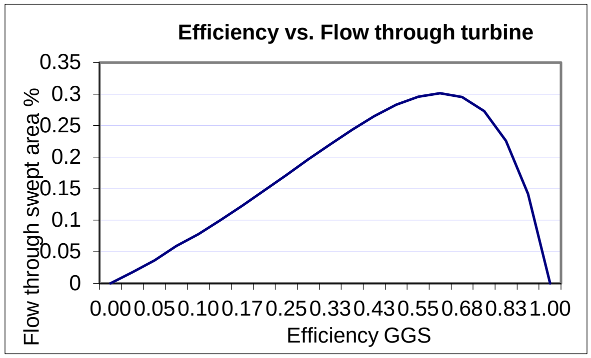


Figure 4.8 Efficiency versus Flow through turbines

Energy is thus lost showing that the fractional power loss increase from 0.33 to 0.67 as the area spanned by the turbines increase from 0 to1 as illustrated in Figure 4.9.

Provision of gearbox amplifies the slow turbine motion rotations to the faster generator rotations. An alternative to using gearboxes, however, is to use a larger generator with permanent magnets.

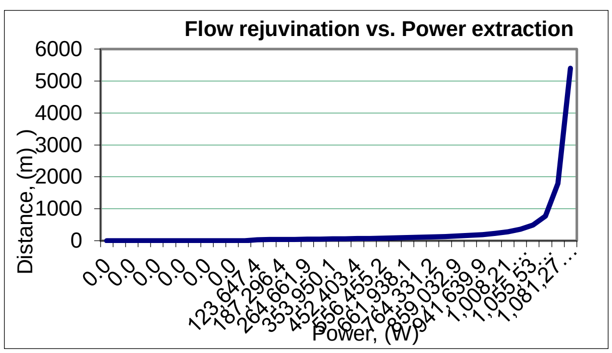


Figure 4.9 Velocity versus Number of turbines

4.7.4 Limitations on energy captured

Investigations were focused on the maximum energy captured and the number of turbines for the identified area of deployment in essence analyse that changes in flow characteristics affect the significant fraction on power extraction modelling. In addition to the economic tidal power extraction viability environmental and turbines effects on the flow and marine life are expected as described in Figures 4.10 – 4.12 & Table 4-8:

i) Fatigue on structures as a result of turbulence

ii) Sediment transport variation

iii) Scouring on the seabed

iv) Vortex shedding

v) Marine organisms

vi) Tidal flow rate

The potential device size analysis is a combination of rotor diameter, support structure size and location in the water column. A restriction to the rotor blade diameter is tip speed ratio whereby high rotational speed reduces performance and increase fatigue.

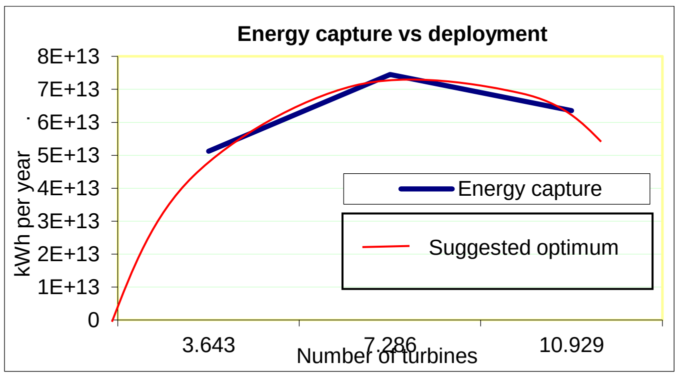


Figure 4.10 Energy capture vs deployment

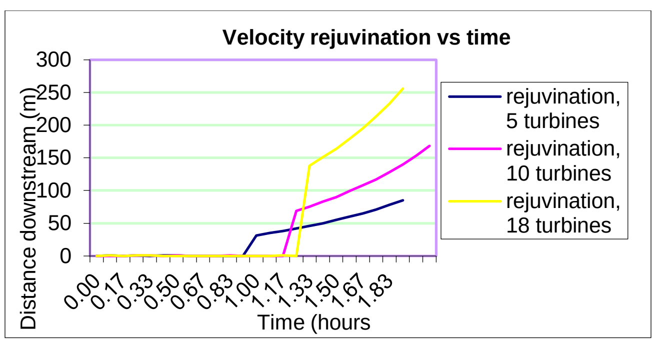


Figure 4.11 Velocity rejuvenation vs time

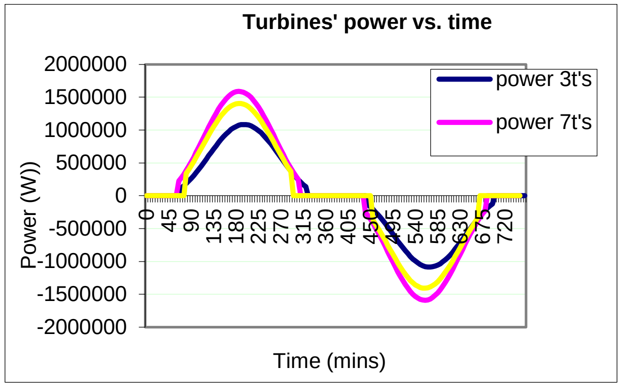


Figure 4.12 Turbines' power versus time

4.7.5 Limitations on simulated power in a channel

Power calculations depend on the following parameters as illustrated in Table 4-8 and Table 4-9:

- Number of turbines
- Significant Impact Factor (SIF)
- Tidal velocity
- Bathymetry and the site dimensions

Table 4-8 Summary of simulated power (kWh) generated per year depending on the number of turbines installed.

Number of Turbines	Power capture per year, kWh		
2 Turbines	$2.0170228623 \times 10^{10}$	2.93×10^{10}	2.5×10^{10}
3 Turbines	$2.017022862 \times 10^{7}$	2.92996637×10^{7}	2.5003247×10^{7}
7 Turbine	$7.2612823042 \times 10^{10}$	1.0548×10^{11}	9×10^{10}
12 Turbines	5.12647×10^{13}	7.4468×10^{13}	6.35×10^{13}

Table 4-9 Selection of Manning's roughness coefficient, n value for channels

Significant impact factor and thus, increased n for obstructions						n (obst)	Representative no. of turbines, and likely no.				
Manning's	0.034354031	Obstruction coefficient for small% blockage				0.00333	10		3.6429771	2	500kW/tur
Manning's	0.037686362	Obstruction coefficient for med% blockage				0.00666	R = 10m		7.2859541	4	500kW/tur
Manning's	0.044936634	Obstruction coefficient for large% blockage				0.013905	R = 10m		10.928931	8	500kW/tur
Reduction in average velocity due to increased n							Turbine rated power in kW, estimated				
Max	1.538674514	Max	1.4026207	Max	1.176316	m/s	Axial	X flow	Osc hydr	Shrouded	
Min	1.243536086	Min	1.1335792	Min	0.950683	m/s	500				
Average	1.398910515	Average	1.275215	Average	1.069466	m/s		500	500	750	
V loss	9.699970871	V loss	17.684546	V loss	30.96568	%					

4.8 Discussion

The Matlab modelling and excel spreadsheets provided a means to estimate the channels potential for sites where only basic information about currents was available, thus the method is well suited to initial assessments. The results can be used to determine whether a channel warrants further measurements or a hydrodynamic model development would be required to estimate values of transport, bathymetry and tidal farm measurements and head loss, [97].

The simulation models for the tidal flow rate assessment of the Kilindini and Lamu channels applied continuity and venturi effect equations which determined the average flow rate for different sites. The models predicted site dimension values which verified the velocity profile of the channel to be accurate within 10% of the Admiralty chart quoted value.

4.8.1 Simulation of Tidal Energy Models

The model was carefully calibrated and validated against pre-existing data and analytical results presented in Table 4-8 and Figures 4.9 & 4.10.

4.8.1.1 The following key features of tidal current speeds were considered:

i) Cut in tidal current speed: at what speed the turbine start generating power

ii) Nominal tidal current speed [66].

iii) Cut out tidal current speed

Selection of suitable tidal stream energy resource sites considered factors ranging from the realistic oceanographic conditions, to the resource potential [4].

4.8.1.2 Assessment of electric power generation from tidal currents, Figure 4.9 [76]

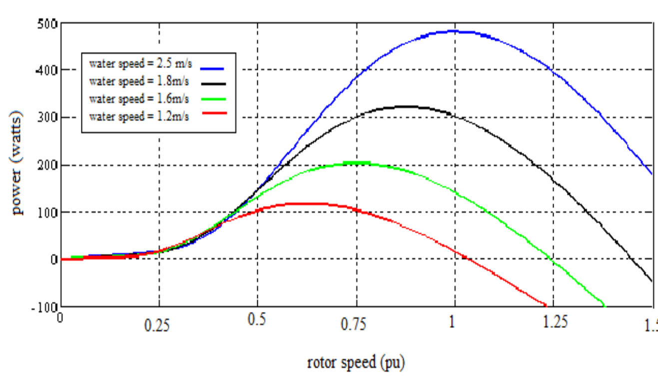


Figure 4.13 Tidal Power Estimates versus speed

Hence realistic oceanographic conditions of the proposed sites could be optimized. The impact of the tides as a practical energy resource was the focus of research, with turbulence, velocity profile, and gearbox, having a significant effect upon the site viability.

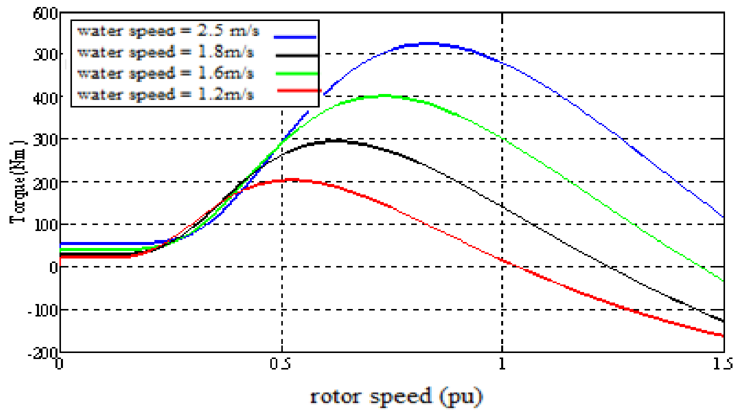


Figure 4.14 Torque versus speed curves for different water speeds

4.8.1.3 Current issues in Marine tidal stream industry:

The modeling exercise raised the following points of interest:

a) Tidal data and site selection Atlases – Insufficient due to site specific data collection

b) Technology design and deployment – Technology development at its infancy stage

c) Transmission and distribution – Yet to be studied

d) Environment impact – Research coverage limited

e) Regulation – Complex

4.8.1.4 Factors of interest

The derivation of uniform flow equations was obtained using the following concepts:

Coriolis effects, Gravitational force, Shear force, and Friction [52].

Flow characterization - project assumed steady flow characterization for ease in computation.

Quantification of fluid dynamics, - applied direct observations, experiments, and existing data

Simulation of tidal velocity profile (Computational fluid dynamics) software model characterized and quantified the velocity profile of the tidal stream energy resource as illustrated in Figure 4.11 & 4-12.

The thesis results provided the tidal resource potential value, broader benefits and economic impact of tidal power development in Kenya.

Environmental effects, such as salinity, depth, temperature, wave propagation (against or for), bathymetry, etc. were considered.

The research concept was of value proposition in its exploration, opportunities and challenges of creating a supply chain for a future tidal energy industry.

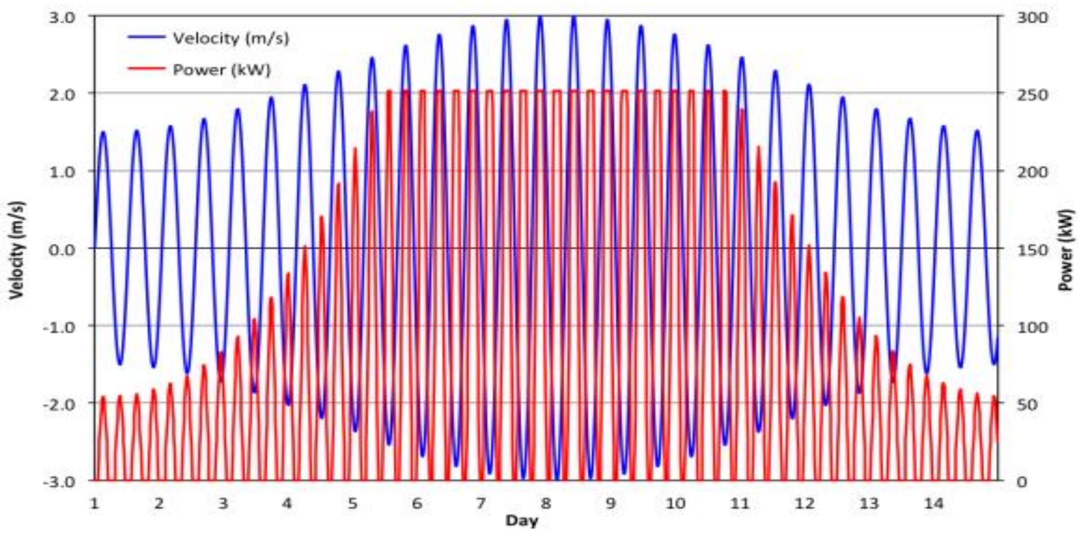


Figure 4.15 Velocity profiles

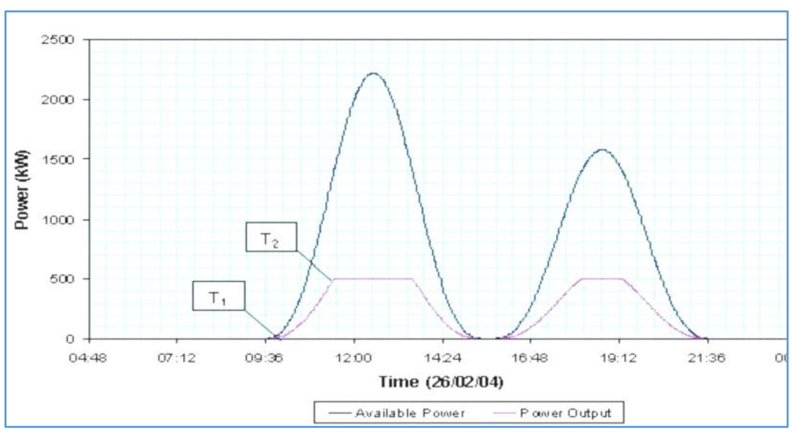


Figure 4.16 Available power versus power output [52]

The power available and the predicted power output of a current turbine is demonstrated over a typical cycle, assuming 0.4 turbine power coefficient, 0.7m/s cut-in speed imposed, and rated speed of 2.4m/s, limiting the maximum power (rated) to a value of 500 kW, Figures 4.11, 4.12 and equation 4-13.

$$\int P(t)dt = \int_{r_1}^{r_2} \left(0.5\eta_1\eta_2 C_p \rho A_0 {V_{Max}}^3 \sin^3 \omega t\right)dt + P_{rated}(T_m - T_2) \tag{4-13}$$

Design and development of technology demonstrated that the total accessibility of tidal power, may improve, with the economic and environmental costs brought down to competitive levels.

Electricity load forecasting being a vital process for planning, expansion in terms of tidal energy utility schedule to meet social, economic and environment factors, including time can be developed to provide end users with safe and reliable power supply. Tides are inexhaustible; hence studies into the feasibility of larger commercial scale Tidal power plants designs have become a viable option.

4.9 Summary

i) Modelling is applicable to predict potential variation to waves and/or water circulation for wave, tidal and current devices.
ii) Energy devices may have localized effects on benthic habitat from electromotive force.
iii) Operational noise and their implications of sound and particle motion would be monitored.
iv) Impact of electromagnetic fields to organisms should be observed
v) Physical interactions on environment e.g. strike around turbines require monitoring

CHAPTER 5: HORIZONTAL AXIS TURBINE OUTPUT POWER RESULTS

5.1 Forces acting on Blade

The widespread horizontal axis wind turbine concept employs the turbine axial induction flow and rotation induction flow concept in the efficient derivative of Kaplan turbine [64], [81]. The turbine blade acts as a brake to fluid flow which induces the velocity in the opposite direction to increase rotation torque as illustrated in the velocity triangle flow, Figure 5.1.

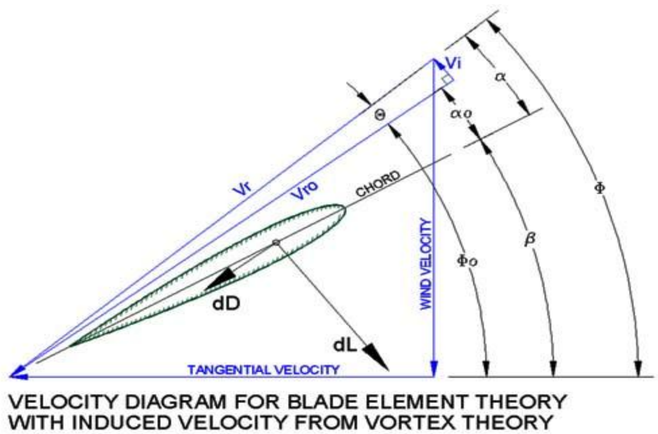


Figure 5.1 Velocity diagram

As the tidal current flow approaches the turbine, part of its energy accelerates the blades, simultaneously exerting axial obstruction energy (which removes from the fluid velocity) and also induce velocity (which adds up to the rotational velocity, $a'\omega_r$).

Thus, $\omega_r + a'\omega_r = V_{ro}$ constitute the new horizontal component with a' equivalent to a rotational induction factor.

$(V_o - aV_o)$, represents the vertical component in which a equals to the axial induction factor.

$$\text{Tan } \vartheta(\text{flow angle}) \quad \frac{aV_o}{a'\omega_r} = \frac{(1-a)V_o}{(1+a')\omega_r}. \qquad (5\text{-}1)$$

$$x^2a'(1+a') - a(1-a) = 0 \qquad (5\text{-}2)$$

$$C_p \text{ is optimal when } a' = \frac{1-3a}{4a-1} \qquad (5\text{-}3)$$

$$16a^2 - 24a^2 + a(a-3a^2) - 1 + x^2 = 0 \qquad (5\text{-}4)$$

For the rotational induction factor, $C_p = a'\omega_r$ (5-5)

Applying the turbine theory, $Power = \int_{r=0}^{R} 4\pi r^3 \rho a(1-a)V_o\omega^2\,dr$ (5-6)

$$C_p = \frac{8}{\lambda^2}\int_{r=0}^{\lambda} x^3 a'(1-a)\, dx \tag{5-7}$$

$$\lambda = \frac{\omega R}{V_o} \tag{5-8}$$

$$x = \frac{\omega r}{V_o} \tag{5-9}$$

$$Relative\ velocity = (1-a^2){V_o}^2(1+a')\omega^2 r^2 \tag{5-10}$$

The blades' induced stream velocity and the higher density of water means that although the blades design are smaller and turn more slowly, they still deliver a significant amount of power. Axial flow rotors are used to drive a generator via a gearbox similar to a hydro-electric turbine. To increase the flow and power output from the turbine additional shrouds or concentrator wings which may be used around the blades to streamline and concentrate the flow towards the rotors. These inventions optimize the blade design in relation to size, capacity, performance, external intrusions and economic aspects.

Tidal spreadsheet generates values for:

- Average flow rate
- Optimal turbine energy extraction
- Formulation of Manning's and Bernoulli numbers to yield friction coefficients when required.

The hydrodynamic force is horizontally projected in parallel to the flow direction also known as Drag force (D), equation (5-11). The Lift (L) is the vertical component of this force expressed as equation (5-12):

$$\mathrm{D} = \frac{1}{2}\rho A C_D V_{Rel}^2 \tag{5-11}$$

$$L = \frac{1}{2}\rho A C_L V_{Rel}^2 \tag{5-12}$$

Normal unit vector in the direction of the wing and tangential respectively:

$$P_n = L\ Cos\ \vartheta + D\ Sin\ \vartheta \qquad (5\text{-}13)$$

$$P_t = L\ Sin\ \vartheta - D\ Cos\ \vartheta \qquad (5\text{-}14)$$

ϑ is vertical unit vector, normal to the freestream direction

Torque on blades is equivalent to direction of rotor rotation

Thrust represents the foundation and structural moments which are proportional to the average sum of velocity at input and exit flow

C_L is the lift coefficient for a wing at a specified angle of attack

5.2 Significant Impact Factor, SIF

The SIF utilization identifies and determines the number of extraction energy units that fit into the tidal stream channel and the effect on resource characteristics [64], [81].

Power versus rotational speed are functions of depth, area, and device's performance within an appropriate limitation to restrain from flow rate interference which may lead to turbulence thus affect topography through sedimentation.

Optimal turbine spacing distance analyses are as presented in Figure 5.2 and Table 5-1 [81]:

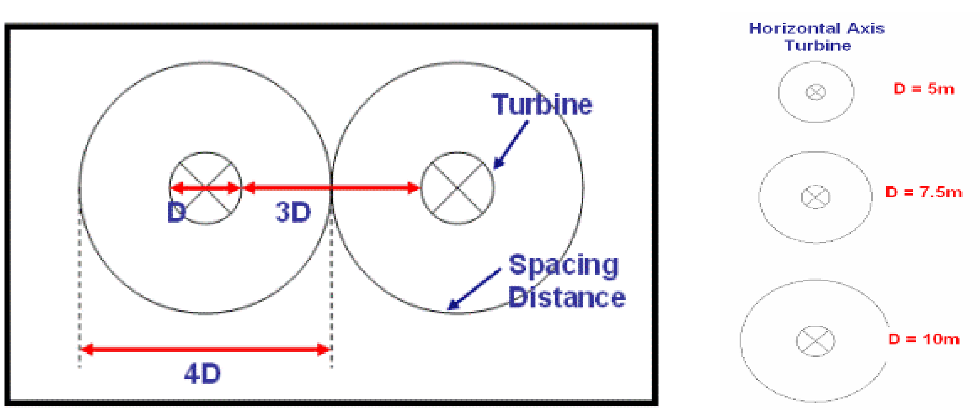


Figure 5.2 Turbine spacing measurements

Table 5-1 Turbine spacing measurements

Type	Horizontal Axis Turbine		
Size(m)	D = 10	D = 15	D = 20
Area (m^2)	78.5	176	314
Spacing	3D	3D	3D
Spacing Distance (m)	30	45	60

Suitable areas for the devices' location and the velocity profile to be fully utilized up to the point where space is exhausted are illustrated in Table 5-2 and Figure 5.3.

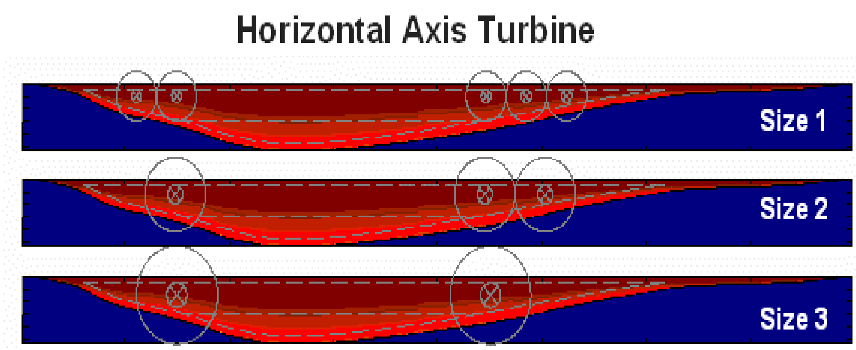


Figure 5.3 Horizontal axis turbine

An estimation of three distinct dimensions and spacing effect on each application inserted into the obtainable space in the profile

Table 5-2 Velocity Profile

	Horizontal Axis Turbine		
Size(m)	D = 10	D = 15	D = 20
Area (m^2)	78.5	176	314
Cp at predominant velocity			
Spacing	3D	3D	3D
Spacing Distance (m)	30	45	60
Number Inserted	5	3	2
SIF reduction in flow (%)	3.62	4.98	5.88
Annual Energy Capture (MJ)	1613.73	2474.49	2940.21
% difference		153	182
Flow recovery (km)	3.39	4.67	5.51

Evaluation of the most satisfactory technology examined for tidal power production, putting into consideration the economics and environmental impacts for a particular velocity profile have been outlined in Figure 5.4.

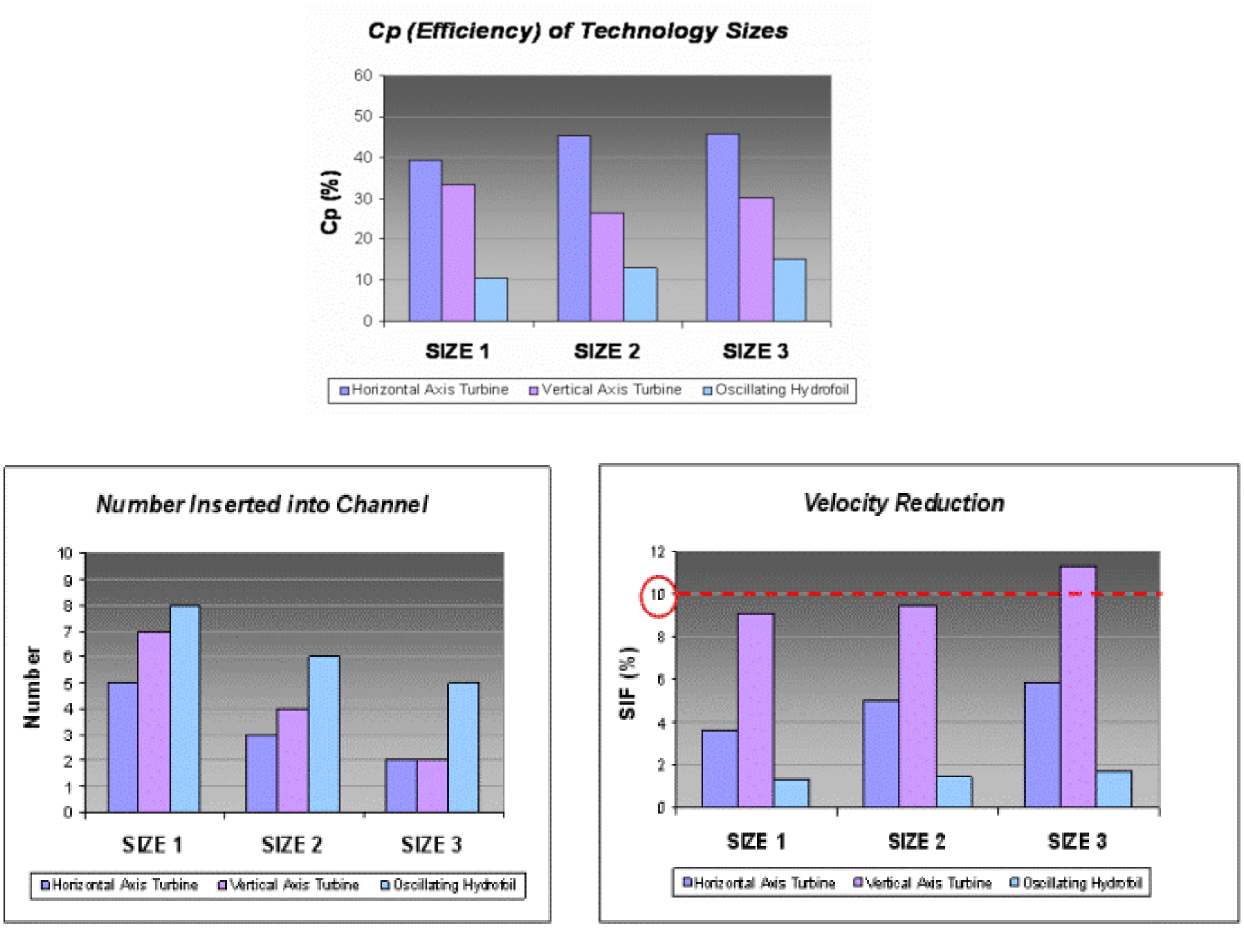


Figure 5.4 Performance Coefficient

Repetition of the whole series of actions is required in order to examine the power output for other profiles in regard to a specified distance along the channel, Figure 5.5.

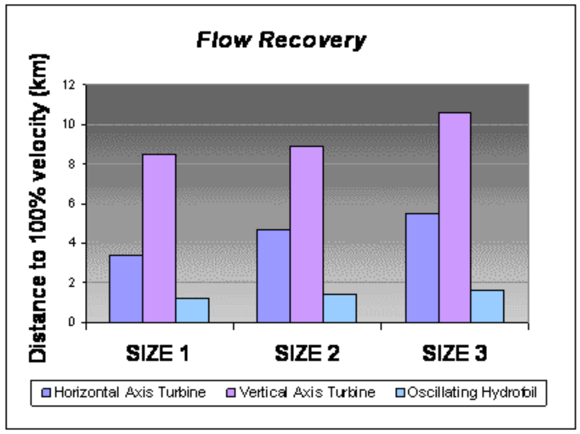


Figure 5.5 Stream Distance

A review of tidal generation profiles taking into account the stream power output capacity value summed up to quantify the entire length of channel device ability as illustrated in Figure 5.6.

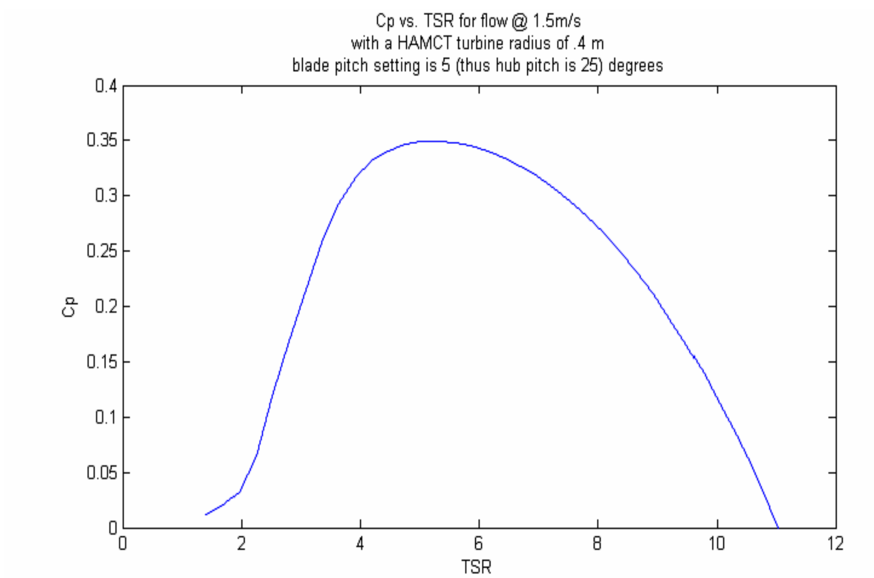


Figure 5.6 Performance coefficient

Full pitch control of marine current turbine extracts considerable power with minimum force exerted on the device due to blades reversal as illustrated in Figure 5.7 [67], [81]

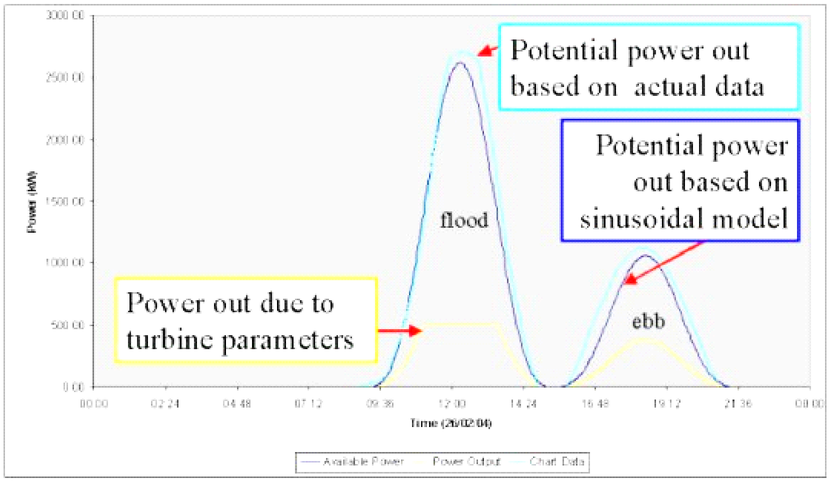


Figure 5.7 Tidal Power Harvest [122]

Figure 5.7 shows the tidal power cycle for 28 days (depth-averaged data), with two spring and two neap cycles for each of the sites namely Mombasa and Lamu. Nominally, for a tidal site to be considered economically viable and suitable for energy extraction mean spring peak velocity should be above 2.5 m/s [68].

The mean depth averaged velocities for both Mombasa and Lamu records are approximately 1.4 m/s. When compared to other sites, Lamu has a higher mean velocity than Mombasa, [55]. However, observations show that the port of Mombasa has three values higher than the values presented here. Already, this initial presentation confirms that the port of Lamu is a strong site and presents a good opportunity for tidal current energy extraction. The ratio of average spring and average neap velocities (Spring-Neap ratio) is 0.7, higher than usual observations of 0.5 where the spring cycle is double the neap cycle. This is of particular interest as a higher ratio indicates that the site has a high overall capacity factor. The use of these metrics estimate becomes useful when comparing spatial variability at other sites or in the process of identifying the most economic site. On the 27th day of the measured time series a maximum wind gust speed of 35 knots was observed in Lamu. Although the wind speed is not very high, the direction coincides with the flow direction of the tidal current of approximately 140°, relative to 0° north. Hourly recorded measured values at this port along with the wind direction are tabulated in Table 5-3 to determine C_p, Figure 5.7 of C_p against tip speed ratio. The meteorological effect reinforces the current velocity and can be identified as the outlier in both tidal envelopes. The wind direction coincides with the principal current direction of Lamu port and therefore the reinforcement is much more evident for this particular set of measurements.

Depth averaged one month time series from Lamu, Table 5.3 and Mombasa, Table 5.4.

Table 5-3 Mean wind speed (knots) [100]

Time (days)	0	5	10	15	20	25	30	0	20
Mean wind speed (knot)	0	5	10	15	20	25	30	0	2

Table 5-4 Tidal current velocity (m/s [100]

Time (days)	0	5	10	15	20	25	30	0	0.5	1	1.5	2	2.5	3
Velocity (m/s)	0	0.5	1.0	1.5	2.0	2.5	3.0	0.0	0.5	1.0	1.5	2.0	2.5	3.0

Figure 5.8 demonstrates horizontal axis marine current turbine outcomes for fluid mass motion from 0.5 to 5 m/s and different speeds up until cavitation. The speeds are categorized as cut in speed (minimum power generated), rising to rated speed (maximum power generated, (P $\propto V^3$) and finally increasing to a furling or cut-out speed (constant power characteristics) where the turbine must stop against damage.

5.3 Results Examination

The rated speed is equivalent to the maximum coefficient of performance and the actual rated amount of turbine power, hence considered to be the optimal operating point of the device. It's possible to raise the power extracted beyond the rated magnitude by application of generators whose production is within 30-40% of the total generated capacity. The following parameters are essential to achieve the energy device control mechanism [113]:

1. Yaw control is the turning of the hub in reference to tidal flow stress direction and can facilitate either downstream or upstream generator construction design features.
2. Pitch angle control using servomotors at the tip of blade, $(i = \vartheta - \alpha)$

$$Tip\ speed\ ratio\ = \frac{Speed\ of\ tip\ in\ relation\ to\ angle\ of\ velocity}{tidal\ velocity}$$

Maximum $C_P\ = Maximum\ TSR$ (Referenced as maximum power point)

3. Electrical Power output control,

$$J\frac{d\omega}{dt} = \frac{P_{M-}P_E}{\omega}$$

(5-15)

$$\frac{1}{2}J(\omega_2^2 - \omega_1^2) = \int_{t_1}^{t_2}(P_{M-}P_E)\text{dt}$$

(5-16)

The challenge is of the effect on TSR with time, Figures 5.8 & 5.9.

4. Braking either active or passive stalling by installing protection mechanism to bring the system to a halt.

   The yaw and pitch angle power control effectively are applicable to horizontal axis turbine unlike for the vertical axis.

5.4 Data Analysis

The probability density distribution function obtained from the average velocity analysis combined with some collected and measured data gives the following outcomes:

$$\int_{t_1}^{t_2}\frac{Vdt}{(t_D + t_L)} = \frac{\sum_{i=1}^{n} V_i}{n}$$

(5-17)

Inspite of the inevitable forecast of tidal currents, the tidal characteristics slightly deviates from the features of the standard model curve. Irregularities are analyzed and form part of the presented results for a resilient and reliable approach.

5.5 Tidal resource characteristics

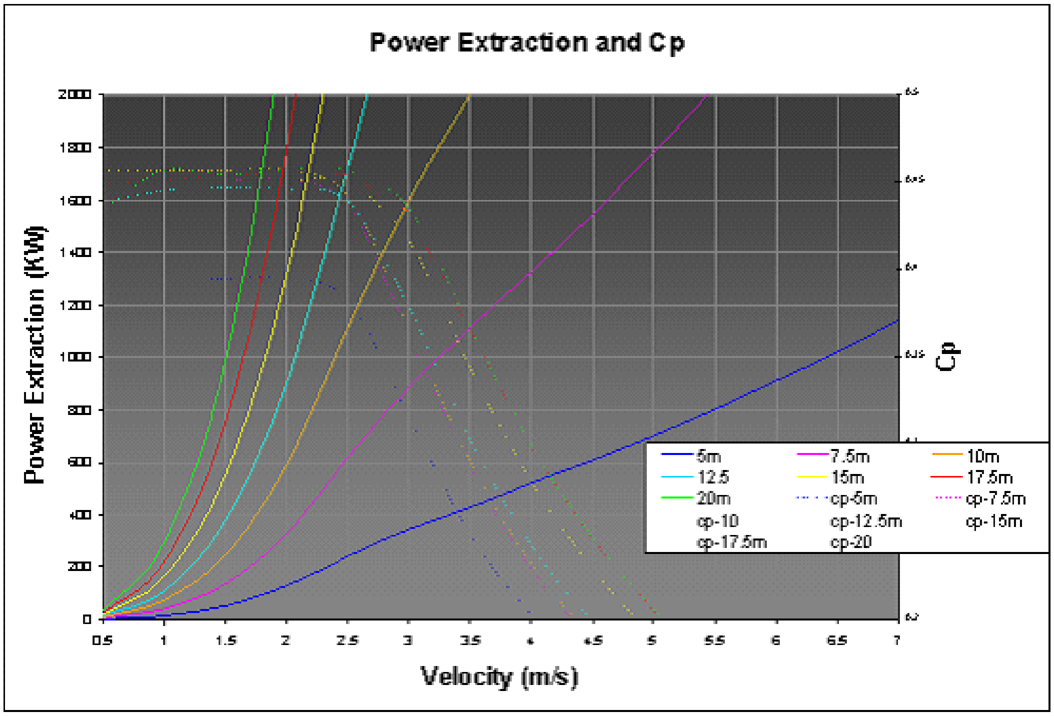


Figure 5.8 Horizontal axis marine current turbine characteristics

An optimal tip speed ratio is necessary in the context that very low rotor speed would allow the fluid to escape through while too fast spin would cause obstruction which appear as a solid wall retarding the rotor angular velocity. When a blade strikes a fluid, turbulence is caused which settles after some time. In case the next blade strikes the fluid at the same position to its predecessor's position an optimal rotational frequency can be realized for effective power extraction.

Effects of high tip speed ratio:

a) Erosion of rotor blade tips

b) Noise

c) Vibration

d) Turbine failure

e) Stiff Shaft

f) Low rotor efficiency

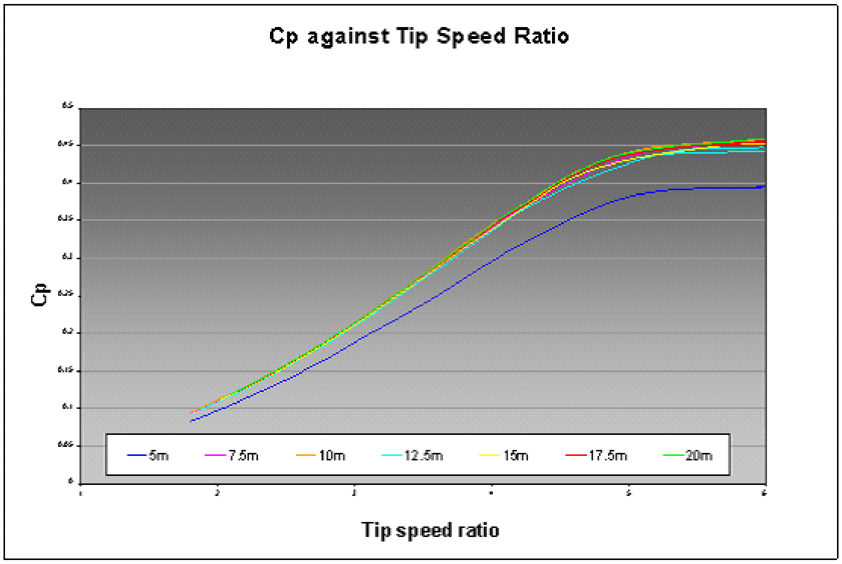


Figure 5.9 C_P versus tip speed ratio

Power /Torque curves illustrate the calculated power as a function of velocity, frequency and other connecting drive train link features to demonstrate varied tested results of measured parameters to exhibit diverse extraction unit characteristics, Figures 5.10 (a) (b) and (c) are given. Designer could make choices on appropriate turbine technology on flow direction and turbine driving force.

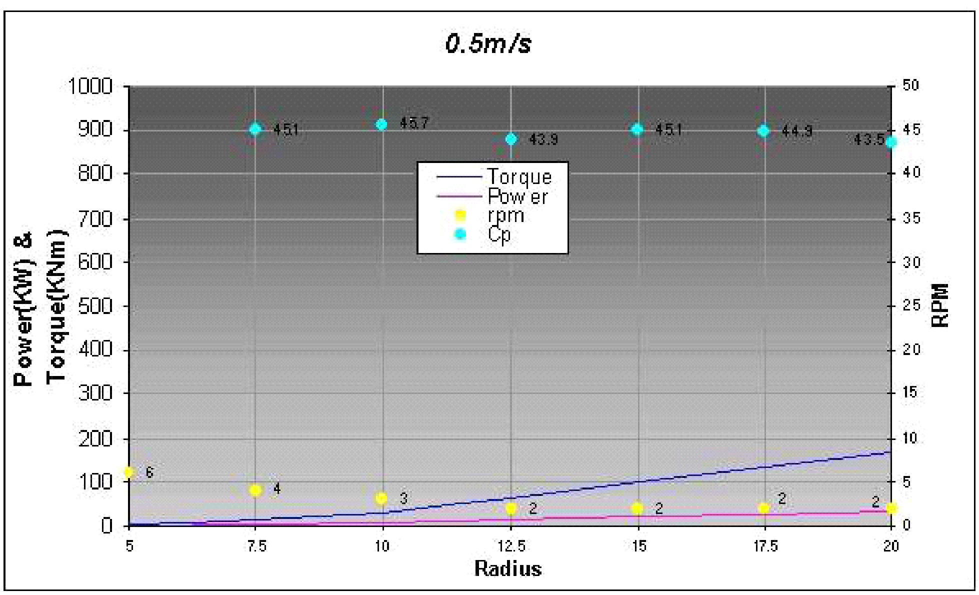


Figure 5.10 (a) power versus torque curves (0.5m/s)

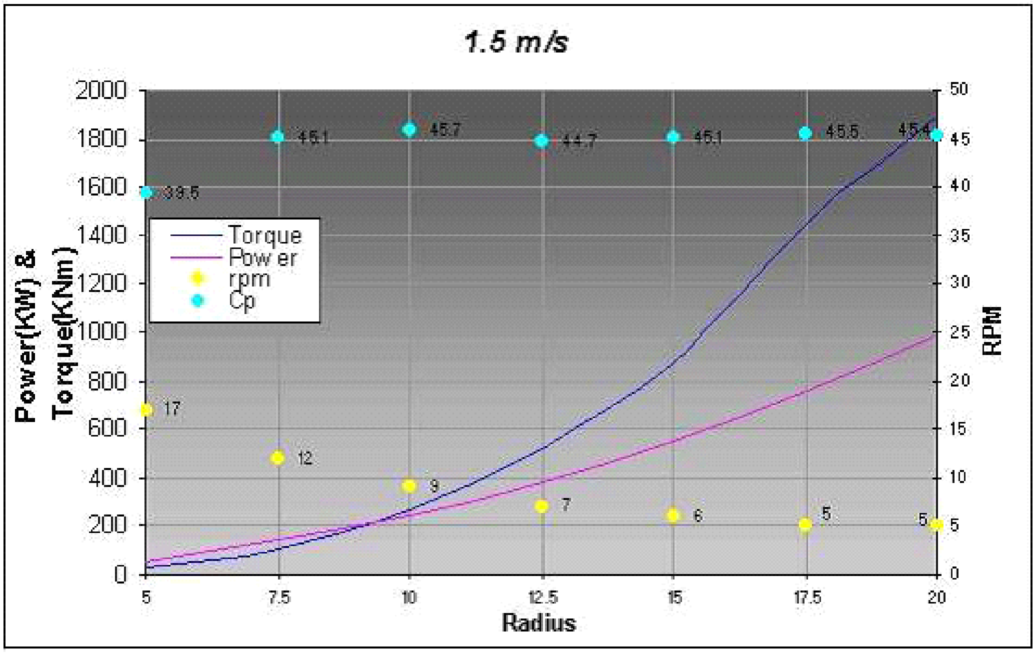


Figure 5.10 (b) Power/ Torque curves (1.5m/s)

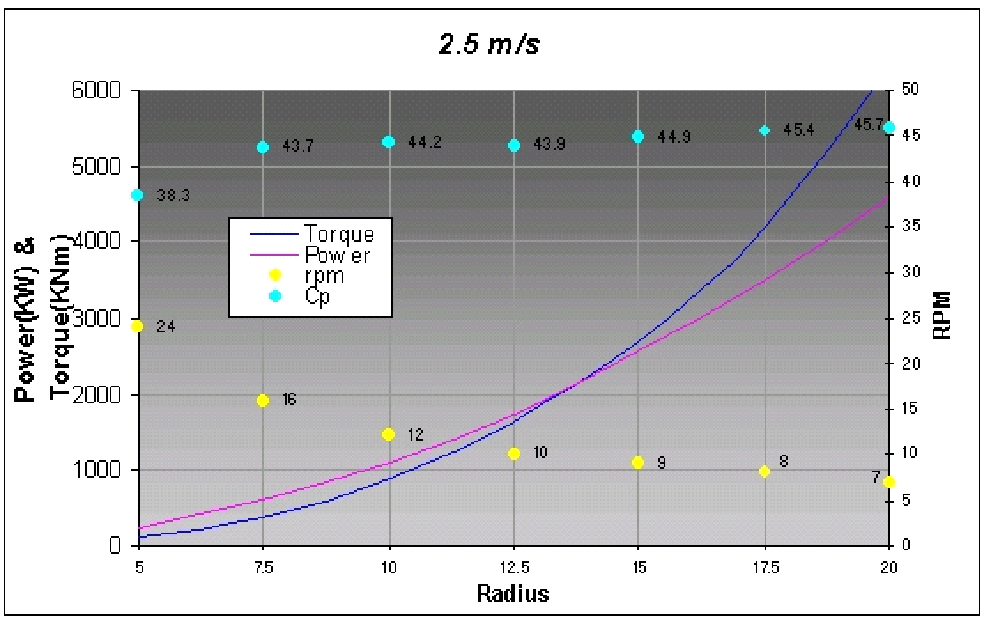


Figure 5.10 (c) Power/ Torque curves (2.5m/s)

Performance power coefficient, C_P defines the turbine characteristics which include torque coefficient, C_{θ}, the thrust coefficient C_T and λ, which are calculated as follows taking into account inlet velocity, turbine features, forces on the blades and the appropriate axis:

$$C_p = \frac{P}{\frac{1}{2}\rho A V^3} \tag{5-18}$$

$$C_\theta = \frac{P}{\frac{1}{2}\rho A R V^2} \tag{5-19}$$

$$C_T = \frac{F}{\frac{1}{2}\rho A V^2} \tag{5-20}$$

$$\lambda = \frac{\omega R}{V} \tag{5-21}$$

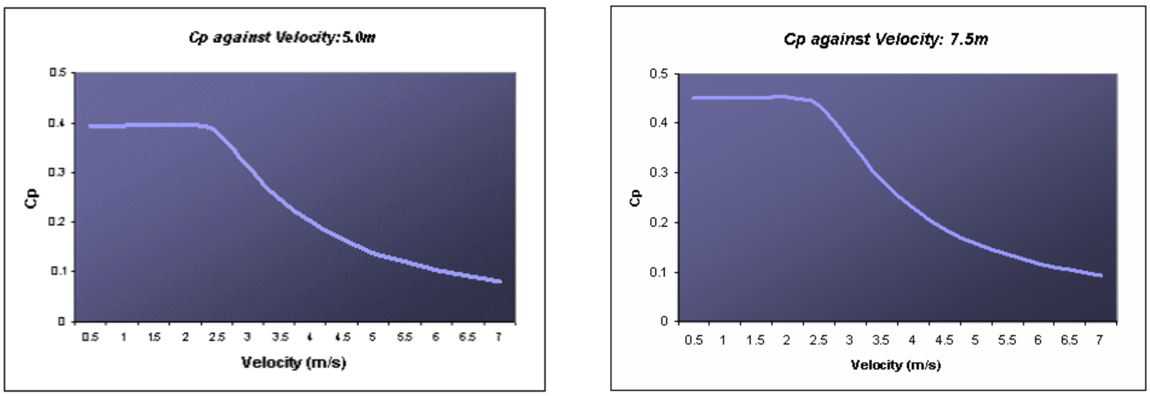


Figure 5.10 (d) Power coefficient against velocity (position < 10m)

This effect is cumulative, as would be expected, adding two portions of highly turbulent fluid to each other will not cancel out the turbulence as each cannot display an exact opposite phase per se; uncertainty promulgates towards different turbulence characteristics as by its nature turbulence is non-symmetrical.

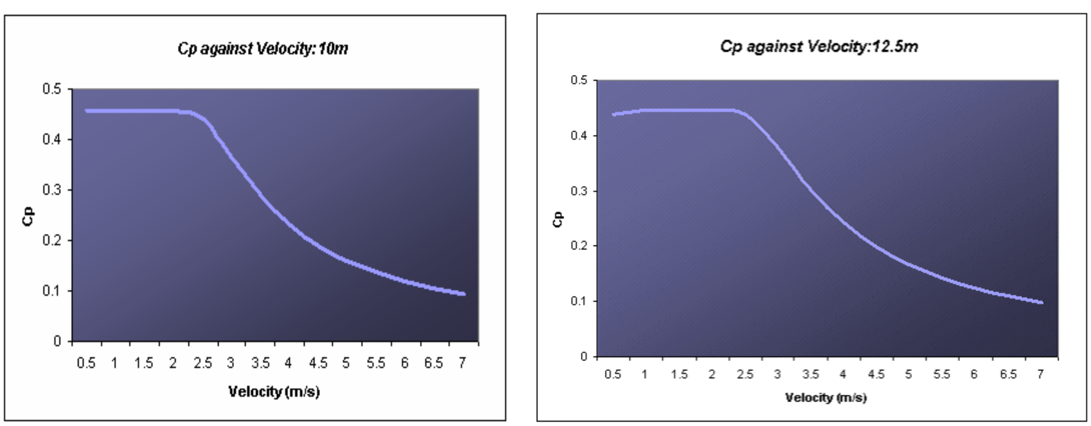


Figure 5.10 (f) Power coefficient against velocity (position > 10m)

Though the irregular disturbed hydraulic fluid motions caused by eddies (turbulence) wake model produced estimated the effective 'spread' radius downstream, the additive blockage effects lead to an increase of backwater: a manifestation of localized head difference across the extraction site. Since the wake model suggested that lateral packing densities can be relatively large [113], it must be regarded in conjunction with the blockage effects.

In open channels, according to Revenue generating unit (RGU), the backwater effect is not as significant as in tidal estuaries or sea lochs, where this can actually increase the power extraction potential due to something of a damming effect, and the SIF could be as much as 50% in such sites**.**

A range of tip-speed ratio were observed and compared by taking flow velocity measurements at different positions in meters (m) from an imagined vertical line as illustrated by Figures 5.10 (g).

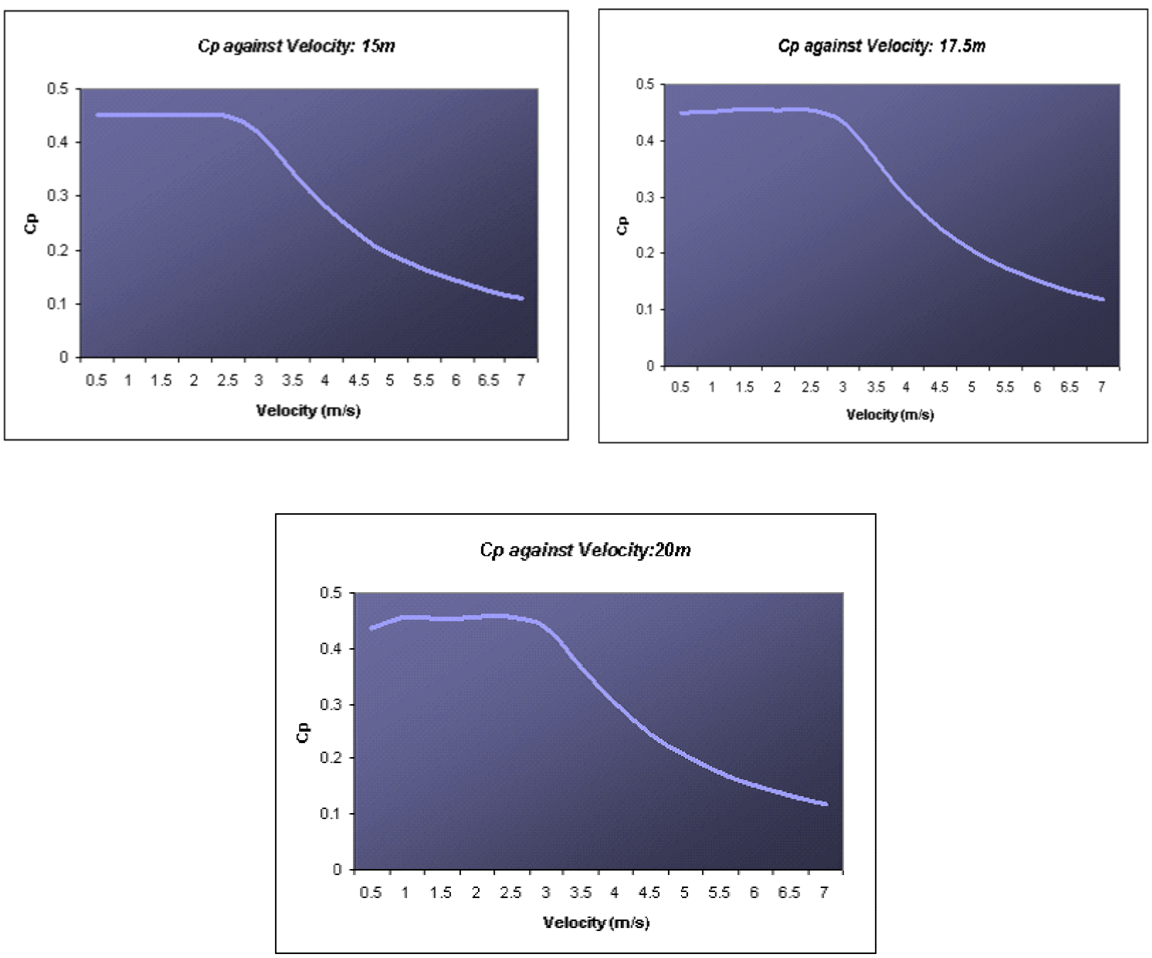


Figure 5.10 (g) velocity time graph position > 15 m

5.6 Marine Tidal features which were crucial for energy capture estimation:
Probability and Statistical Distribution, Figure 5.11.

Ocean resource characteristics in terms of quantity, velocity and topography

Turbine characteristics

Capacity factor

Choice of generation machine design

$$\text{Tip speed ratio, } \lambda = \frac{rotor\ tip\ speed}{Tidal\ current\ speed} = \frac{\omega r}{V}\ , dimensionless$$

(5-22)

Probability and statistical distribution represents when overall magnitude of a vector is related to its direction components in the probability density function in equation (5-23)

$$f(V) = k\frac{V^{k-1}}{c^k}e^{-(V/c)^k}$$

(5-23)

Tidal energy is analyzed into its two- dimensional vector components, (k and c) of Weibull distribution for example, Rayleigh (a single parameter c) and Exponential distribution (two parameters k and c).

Rayleigh distribution is a special case ofWeibull distribution, setting k=2

$$\text{Ray leigh distribution}, (k = 2): \qquad f(V) = \frac{2V}{c^2}e^{-(V/c)^2} \qquad 0 \le V < \infty$$

(5-24)

Exponential distribution is a special case ofWeibull distribution, setting k=1

$$\text{Weibull distribution:} \qquad f(V) = \frac{1}{c}e^{-(V/c)} \qquad 0 \le V < \infty$$

(5-25)

Where c = positive scale factor with dimensions of velocity and k = shape factor which is dimensionless, chosen to fit the data

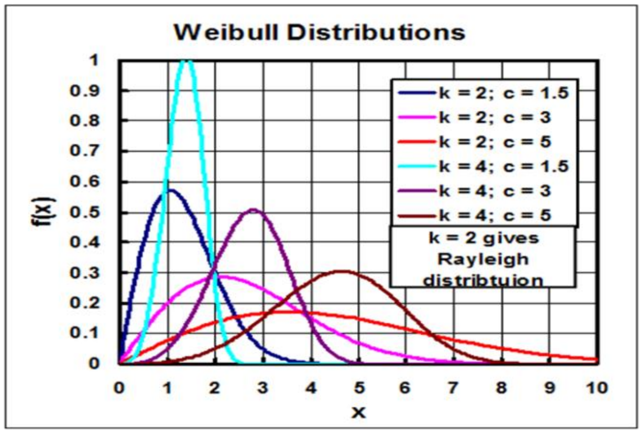


Figure 5.11 Weibull Distributions

Average Power in the Tide

$$\overline{P(V)} = \int_{V_{min}}^{V_{max}} P(V)f(V)\,dV = \int_0^\infty \frac{\rho A V^3}{2} f(V)dV = \frac{\rho A}{2}\int_0^\infty V^3 f(V)dV = \frac{\rho A V^3}{2} \tag{5-26}$$

5.7 Project costing estimates

Time is ripe for exploitation of ocean energy technology for commercialization of industrial and social welfare as shown in Table 5-5. Focus should be on technology investment and building of prototype equipment for comparison of different ocean energy applications. Political subsidy or intervention and government support towards attracting foreign investors is a matter of urgency for the ocean energy investment to gain a foothold. Public awareness, negotiation of ocean energy exploration, economic policy and aesthetics (impact) are crucial factors in need of attention. The present industry needs to gain a political voice and investor confidence from promising returns in regard to construction of actual working systems. The evaluation system has no installed base or technical foundation for benchmarking, because scientists, engineers and developers have not proven viability of ocean energy concrete foundation plans with strategic research design, education and building operational facilities [34], [51], [112].

The tidal energy may be described as a combination of hydraulics, P_H turbines, P_R and electrical, P_E processes. The power and voltage transfer relationships (Equations i to v) describes the hydraulic flow, e_H, rotor, e_R electrical, e_E and overall, e efficiencies respectively:

$$e_H = \frac{P_R}{P_H} \quad (5\text{-}27)$$

$$e_R = \frac{P_S}{P_R} \quad (5\text{-}28)$$

$$e_E = \frac{P_E}{P_S} \quad (5\text{-}29)$$

$$e = e_H e_R e_E = \frac{P_E}{P_H} = \frac{V_R}{V} \quad (5\text{-}30)$$

The overall tidal energy efficiency determines the hydraulic power across the capture area of device:

$$P_H = \frac{1}{2} e\rho A V^3 \quad (5\text{-}31)$$

The tidal power resource potential along Kenyan coastline for power density versus current speed analysis per unit horizontal area is shown in Tables 5-5 to 5-11:

Table 5-5 Power Density at several Current Speeds [125]

Current speed, m/s	Power density, kW/m^2 Horizontally
0.5	64
1.0	513
1.5	1730
2.0	4100
2.5	8008
3.0	13836
3.5	21973
4.0	32800
4.5	46702

Table 5-6 Bill of Quantities, BOQ [99]

Task	Detailed Task Description	Unit	Unit Cost (Ksh)	Total Cost (Ksh)
TURBINE DESIGN	Tidal turbine detailed design and productivity calculations	1	30	**20,000,000**
	Wave device hydrodynamic modelling and the development of equations of motion	1	6	
	Pneumatic turbine material studies for oscillating water column systems	1	12	
RESOURCE AND SITE ANALYSIS	Wave and tidal hydraulic modelling, array analysis and useable resource analysis including interpretation of ADCP data	1	12	**20,000,000**
	Site selection and constraints analysis including deployment site risk matrices	1	6	
	Monitoring and survey management (including ecological, geotechnical, geophysical, met ocean and noise)	1	14	
	Cable routing and landfall studies	1	28	
ENVIRONMENTAL	Environmental evaluations	1	3	**20,000,000**
	Environmental scoping and impact assessment	1	3	
	Consents compliance	1	2	
INSTALLATION DESIGN	Design of specific piled foundation and gravity base structures	1	35	**10,000,000**
	Development of detailed deployment and retrieval methodologies	1	12	
	Concept design of bespoke installation plant and barges	1	30	
	Detailed design of subsea support structures for tidal energy devices	1	6	
	Design of innovative piled foundation installation plant	1	12	
	Integrated overall design approach to foundations, support structure, installation/retrieval frames, deployment procedures and marine plant requirements	1	18	
	Finite Element analysis for dynamically loaded structural frames including fatigue considerations and resonant frequency analysis	1	12	
	Production of design reports for submission to certifying bodies including NEMA, County government, etc	1	6	

Table 5-6 Bill of Quantities, BOQ [99] , continuation

Task	Detailed Task Description	Unit	Unit Cost (Ksh)K	Total Cost (Ksh)
FABRICATION AND DEPLOYMENT SUPPORT	Compilation of fabrication drawings and specifications	1	21	**20,000,000**
	Negotiation with fabricators and marine contractors	1	6	
	Supervision of fabrication process, inspection and sign off	1	120	
	Design and project management support during construction and installation process	1	120	
CONTRACT AND PROCUREMENT SERVICES	Procurement advice and management services utilizing NEMA, NCCA, County government forms of contract	1	6	**10,000,000**
	Production of Contract Documentation including amended Contract terms, Specifications and Bills of Quantities for fabrication and construction contracts	1	6	
	Contract administration and project management services	1	120	

Table 5-7 Tidal energy budget

Task	Detailed Task Description	Time frame (Days)	Unit Cost (Ksh)	Total Cost (Ksh)
1	Mechanical and Electrical components will take about (30% of total cost.)	**90**	**300**	**30,000,000**
2	Material and structures will take about (20% of total cost)	**120**	**200**	**20,000,000**
3	Site, Environmental monitoring and Permission will take about (20 % of total cost)	**30**	**500**	**20,000,000**
4	Mooring and foundation will take about (15% of total cost)	**30**	**500**	**15,000,000**
5	Installation and commissioning will take about (10% of the total coast)	**30**	**250**	**10,000,000**
6	Transmission and grid connection will take about (5% of the total cost)	**30**	**100**	**5,000,000**
TOTAL		**310**		**100,000,000**

Table 5-8 Project Costing Estimates

Project Costing Estimates					
Component	**Details**		**Pessimistic**	**Base**	**Optimistic**
Structure	Cost of main structure.	USD $	7,200,000	6,720,000	6,240,000
Foundations/moorings	Cost of all foundations, anchors or moorings.	USD $	2,400,000	2,240,000	2,080,000
Control/instrument	Control and monitoring instruments.	USD $	1,200,000	1,120,000	1,040,000
Power Take-off	Power Take-Off costs including all mechanical and electrical components.	USD $	2,400,000	2,240,000	2,080,000
Grid connection	Grid connection.	USD $	1,200,000	1,120,000	1,040,000
Installation surveys	Surveys.	USD $	600,000	560,000	520,000
Installation of structure	Installation of the structure (including hire of vessels).	USD $	6,000,000	5,600,000	5,200,000
Installation of mooring	Installation of the mooring (including hire of vessels).	USD $	3,000,000	2,800,000	2,600,000
Installation of grid connection	Installation of the grid connection from farm to shore and onshore work (including hire of vessels).	USD $	1,500,000	1,400,000	1,300,000
Commissioning	Commissioning of farm.	USD $	1,500,000	1,400,000	1,300,000
Management and other	Management, insurance and other costs.	USD $	3,000,000	2,800,000	2,600,000
Capital cost: Total installed		**USD $**	**30,000,000**	**28,000,000**	**26,000,000**
Planned maintenance	Planned maintenance and inspection.	USD $ /annum	3,000,000	2,700,000	2,400,000
Monitoring/Control	Monitoring/Control of energy production and condition monitoring.	USD $ /annum	750,000	675,000	600,000
Unscheduled repair	Unscheduled repair.	USD $ /annum	750,000	675,000	600,000
Rent	Rent, both land and sea.	USD $ /annum	240,000	225,000	200,000
Insurance	Insurance.	USD $ /annum	250,000	225,000	200,000
Operating costs: total annual		**USD $ /annum**	**4,990,000**	**4,500,000**	**4,000,000**
Total decommissioning costs	**Incurred after project life has ended.**	**USD $**	**5,000,000**	**4,500,000**	**4,000,000**

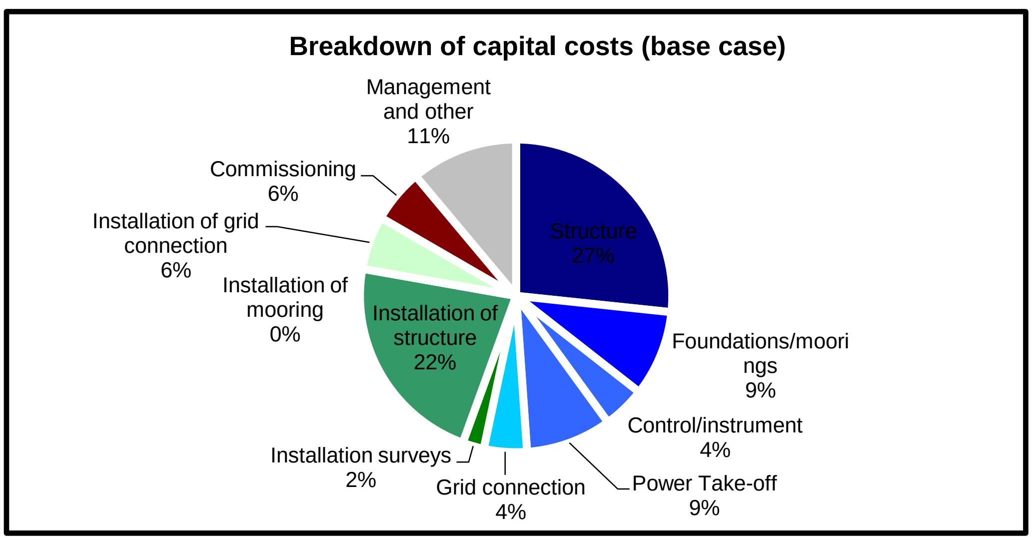


Figure 5.12 Breakdown of capital costs

Table 5-10 Cost of Energy

Cost of energy

	Pessimistic	Base	Optimistic	
Life	25	**25**	25	years
Capital cost	$30,000,000.00	**$25,202,800.00**	$26,000,000.00	
Operating cost	$5,000,000.00	**$678,825,000.00**	$603,400,000.00	/year
Decommissioning cost	$5,000,000.00	**$4,500,000.00**	$4,000,000.00	
Annual energy production	39,087,120	**45,916,416**	52,428,600	kWh/y
Indicative cost of energy				
Discount rate 8%	20,156.91	**1,483,668.76**	1,155,648.56	p/kWh
Discount rate 15%	24,725.48	**1,486,930.09**	1,158,606.15	p/kWh
Capacity factor excluding transmission losses				
Device	20%	**30%**	35%	
Farm	35%	**30%**	25%	
Capacity factor including transmission losses				
Farm	22%	**26%**	30%	

The indicative cost of energy quoted here is based on a simplified discounted cash flow analysis. A more rigorous estimate could be made by considering all income and expenditure at all stages of the project life.

The pessimistic and optimistic values are a straightforward combination of all the pessimistic and optimistic totals respectively. This is a simplistic approach for illustration only. A more rigorous approach might produce a lower overall uncertainty (range of costs) than indicated here.

Table 5-11 Current charges of Energy

Tariff	Charges (KES)		
	Fixed charge	Energy charge (per kWh)	Demand charge (per kVA)
DC (Domestic, 240 V)	150	First 50kWh: 2.50 50 to 1 500kWh: 12.75 Thereafter: 20.57	n/a
SC (Small Commercial, 240 V)	150	13.5	n/a
CI1 (Commercial, 415 V)	2 500	9.2	800
CI2 (Commercial, 11 kV)	4 500	8	520
CI3 (Commercial, 33 kV)	5 500	7.5	270
CI4 (Commercial, 66 kV)	6 500	7.3	220
CI5 (Commercial, 132 kV)	17 000	7.1	220
IT (Domestic water heating)	150	13.5	n/a

5.8 Summary

High resolution numerical assessment on tidal energy, fatigue on converters due to loading, and turbines exposure being durable enough to survive the hostile aquatic environment are subjects of concern. .

Total cost of marine energy technologies consist of investment and operation costs.

Although tidal power schemes have a high capital cost they have a low running cost.

Ultimately, as technology advances the cost comes down, as it inevitably will with continued investment, tidal stream farms will be laid on the seafloor or floated above it.

One field of ongoing research is determining the proper spacing and siting of the turbines to maximize power output.

CHAPTER 6: OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS

6.1 Observations on the marine tidal stream energy description and validation

6.1.1 Future Demand for marine energy capability

Electrical generation capacity of a country is strategically important for the economy. The industrial growth status predicts that an electrical energy increase by 2040 and further hydro-geothermal and wind development would still be unable to meet future demand. In the long term, marine energy is a potential resource with technology, performance and cost competitiveness as key challenges which must be addressed for future growth and investment towards achieving government target of 90% renewable electricity generation by 2025.

6.1.2 Wave and Tidal Resource

Watamu location in Kenya was identified to possess a high potential (MSS $\geq 2m/s$) for tidal current turbines [108].

6.1.3 Expertise for site assessment

KMFRI, NOAA, UNESCO, among others offer an excellent pool of expertise that could assist in identifying specific tidal and wave energy sites. Further detailed analysis is required to ascertain detailed bathymetric data on localized conditions including physical environmental attributes, channel depth and underwater topography (including type of sea bed and profile). Detailed analysis is crucial in determining optimum site selection and deployment.

6.1.4 Technical Maturity

Marine energy converters' survival, reliability and engineering standards in relation to design and operation as compared to other renewable energy systems should be objective and competitive for optimum cost reduction with respect to pre- and post-investment impact to the environment. Marine energy technology should be given attention in Kenya. Development of, and adherence to comprehensive well-proven technical standards must form a vital part of any future development.

6.1.5 Cost reduction

For marine energy extraction principle viable concerns on budget, modeling and implementation are under investigation. Cost estimates, market conditions and grid integration would decrease with deployment and increased installed capacity.

The computational model of this research requires further development by adding an active form of controller for modeling the water turbulence, adding the dynamic in flow to the hydrodynamic system and components. Different design load cases as prescribed by International Electro technical Commission, IEC standard for wind turbine analysis can be used here.

6.2 Discussion on procedure on the characterization of tidal flow

6.2.1 Identification of the appropriate technology and matching it to the resource proved to be a challenging process.

The methodology was presented ranging from resource profile, site selection, design development, power scale rating, design optimization, deployment, economies of scale, environmental and SIF limitations which needed to be balanced hence a critical process.

6.2.2 Uniform velocity distribution, quite promising for deployment nearer to the seabed

Concern on the general limitations was the extent of proximity in which the devices could efficiently capture and generate energy having been specified, ranging from 25% of LAT to within 5 metres. It was discovered that roughness and shear movements have lesser effect on the flow rate than previously expected. The equipment extraction device mechanisms could as well be installed around 2 metres of the channel or seabed. Due to less civil works involved, stream generation has minimum impact to the environment which provides adequate levels of production and transport investment capacity due to access to services at stable costs.

6.2.3 Uni-directional technology is a feasible option, since defining the characteristics of flow for a site cannot be presumed to be equally bi-directional

Generally tidal flow models assume a typical sinusoidal ebb and flood model approximation, though out of phase tidal flows sometimes can cause intermittent harmonics and unidirectional flow in the channels due to positioning of landmasses.

6.2.4 Site geometry in the lateral sense, was generally the limiter where SIF dictated longitudinal spacing

An assumption that with technology development, the equipment could be deployed to deeper depths greater than 30m increasing extracted energy considerably, however results demonstrated that the extraction would be limited by SIF. A SIF approaching 9% in the preliminary case study was achieved due to depth limitations.

Tidal stream power distribution over a wider area makes it economically difficult to harness.

6.2.5 Velocity recovery distances are much larger than expected especially after extraction of energy

Rejuvenation distances are more; therefore tidal farms require substantial space at marine sites to enable for implementation of this flow rejuvenation.

6.2.6 Lower SIF is preferable and higher number of smaller or alternative devices taking into consideration their dependence on costs of technology

Swift flow rejuvenation, increased flow velocities and higher average power production, are enabled improving the economic viability and commercial competitiveness of tidal farms.

6.2.7 SIF and their influence are dictated by Economic drivers and levels of adherence

Economic factors dictate, similar to wind farms.

(Rejuvenation is the state of a river which has renewed energy and increased erosional capacity)

6.3 Conclusions

Waves influence on tidal energy resource though not accounted for, generate stresses on turbine infrastructure at an oblique angle and must be considered as an environmental impact. The variation on the tidal energy quantities due to storms was evident hence a coupled wave and tide hydrodynamic model is vital. Marine current energy is one of the appropriate and sustainable means of solving increasing global electric power demand, dwindling natural resources and reducing environmental pollution from fossil fuel generation schemes. Tidal data on physical observations for different sites demonstrates the real oceanographic profile, support structure and performance.

With the current status of the developing marine energy industry, tidal velocity distribution and current motion investigation s can be considered [27]. In contrast to other clean sources, such as wind, solar, and geothermal, tidal stream energy can be securely predicted for centuries into the future; accurate power outputs can also be calculated in advance allowing for ease of integration with existing electricity grid.

The predictability of tidal current energy may establish a meaningful asset towards energy contribution to an emerging Kenya Governments renewable tidal stream industry. However, integration of this new energy generation technology will require detailed planning and a thorough understanding of the resource and its variability, as the identified sites and power generation scenarios indicate no potential for load base generation. Locations of high potential for tidal stream energy were observed, although unlikely to currently attract attention, there are propitious future opportunities for the coastal region [114]. In this regard, the project would effectively progress the Islands and isolated states of the Western Indian Ocean [20].

6.4 Recommendations

6.4.1 Observations proposed to researchers, policy makers and developers of marine tidal current industry:

a) Further modeling of flow rejuvenation takes a prominent part in the entire energy extraction hence will be the most important element of requisite farm deployment. In this regard there are significant distinctions which exist between the marine and wind power industry.

b) In the likelihood that SIF legislation are given considerations, developers of tidal energy become aware of cross and downstream impacts

Blockage characteristics of individual device bear a relationship between, single spacing, single power coefficient, SIF and total site output power. Developers should not only know of a simple case like the larger the device, the higher the efficiency and the more powerful. Although larger turbine size has equivalent largest power outputs and power coefficients to some proportion, increased packing density, cost, and space, complicates device deployment in relation to inefficient space utilization, expensive cabling and management costs of large tidal farms.

c) Frequent information sharing and circulation will aid design optimization and analyzing of cost in relation to device, deployment, station foundations and grid integration.

d) Improved detailed techno-economic modeling is vital in order to provide accurate outcomes.

Presently, there was scarce economic data on output power, cost and payback time in a bid to validate economic viability of models and provide precise indication for appropriate optimum technologies, more detailed cost analysis expected to promote methodology employed and shift the choice in favor of optimum equipment.

6.4.2 Existing technology options are comparable hence site specific evaluation necessary:

The public in Kenya has remained unconcerned with ocean energy due to performance characteristics and development indicators. However, concern parameters such as import dependence and cost volatility consistently emerging would favorably establish energy policies strategies to engage general public and energy investors.

Due to its large fixed costs, not only in plant development, but in education, marine environment and regulatory infrastructure the industry is not just an ordinary investment.

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APPENDICES

APPENDIX A: MATLAB Code for Variation of Cp with μ and P

```
%Appendix (A): MATLAB Code for Variation of Cp with μ and P
%Cq and Cp curve as a function of Lambda
close all;
clear all
clc;
J_T=1270; %Moment of inertia
pr=20000; %Rated Power
r=5; %radius of the rotor
rho=1.225; %density
uc=6.5; %cut in speed
ur=11.7; %rated speed
uf=24; %Furling speed
omega=105; %angular speed
cpm=0.2596; %maximum cp
lamdam=5; %tip speed ratio at maximum cp
um=11; %wind speed at maximum cp
cpr=pr/(0.5*rho*ur^3*r^2*pi);
% Operation or linearization point
lamb_op=7; %operation tip speed ratio
u_op=7.5; %operation wind speed
cp_op=0.2; %operation Cp
cq_op=cp_op/lamb_op; %operation Cq
% Solve the A and B coefficients
A_B=inv([((um/uc)-1)^2 ((um/uc)-1)^3;((um/ur)-1)^2 ((um/ur)-1)^3])*[1;1-cpr/cpm];
A=A_B(1,1);
B=A_B(2,1);
%Find the Cp and P variation
uu=(uc:0.01:uf)’;
u=(uc:0.01:ur)’;
u1=(ur+0.01:0.01:uf)’;
for i=1:size(u)
for k=1:2;
beta(k)=0;
cp(i,k)=cpm*(1-A*((um/u(i))-1)^2-B*((um/u(i))-1)^3);
p(i,k)=0.5*rho*pi*r^2*cp(i,1)*u(i)^3;
lamb(i,1)=r*omega*2*pi/(60*u(i));
cq(i,k)=cp(i,k)/lamb(i,1);
end
end
for k=1:size(u1)
j=k+521;
for l=1:2
beta(l)=0;
cp(j,l)=(cpr*ur^3)/u1(k)^3;
```

```
p(j,l)=0.5*rho*pi*r^2*cp(j,1)*u1(k)^3;
lamb(j,1)=r*omega*2*pi/(60*u1(k));
cq(j,l)=cp(j,l)/lamb(j,1);99;
end
% Plotting time!!!!!
Figure(1)
plot(uu,cp(:,1)),grid;
title(‘Figure 1: Graph of Coefficient of performance, cp as a function of water speed’);
xlabel(‘water speed (m/s)’);
ylabel(‘C_p’)
figure(2)
plot(lamb,cp(:,1)),grid;
title(‘Figure 2: Graph of Coefficient of performance, cp as a function of tip speed ratio’);
xlabel(‘tip speed ratio’);
```

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```
ylabel(‘C_p’)
figure(3)
plot(uu,p(:,1)),grid;
title(‘Figure 3: Graph of Rotor Mechanical Power as a function of water speed u’);
xlabel(‘water speed (m/s)’);
ylabel(‘Rotor Mechanical Power’)
figure(4)
plot(lamb,cq(:,1)),grid;
title(‘Figure 4: Graph of Coefficient of torque, cq as a function of tip speed ratio’);
xlabel(‘tip speed ratio’);
ylabel(‘C_q’)
figure(5)
surf(beta, lamb, cp);
AXIS([-2 2 1 15 0 .6])
title(‘Figure 5: Graph of beta, lamda versus the coefficient of performance’)
xlabel(‘beta’)
ylabel(‘lamda’)
zlabel(‘Cp’)
figure(6)
surf(beta, lamb, cq);
AXIS([-2 2 1 15 0 .06])
title(‘Figure 6: Graph of beta, lamda versus the coefficient of Torque’);
xlabel(‘beta’)
ylabel(‘lamda’)
zlabel(‘Cq’)
dcq_dlamb=-(cpm/lamb_op^2)*(1-A*((um/u_op)-1)^2-B*((um/u_op)-1)^3);
%(dCq/dlambda)
alpha=(1/J_T)*0.5*rho*pi*r^3*u_op*(2*cq_op-lamb_op*dcq_dlamb);
%alpha
gamma=(1/J_T)*0.5*rho*pi*r^4*u_op*dcq_dlamb;
%gamma
```

APPENDIX B: Manning's n for channels

Manning's n for Channels (Chow, 1959)

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at flood stage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. same as above, but more stones and weeds	0.030	0.035	0.040
c. clean, winding, some pools and shoals	0.033	0.040	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.050
e. same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. same as "d" with more stones	0.045	0.050	0.060
g. sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. bottom: cobbles with large boulders	0.040	0.050	0.070
3. Floodplains			
a. Pasture, no brush			
1.short grass	0.025	0.030	0.035
2. high grass	0.030	0.035	0.050
b. Cultivated areas			
1. no crop	0.020	0.030	0.040
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.030	0.040	0.050
c. Brush			
1. scattered brush, heavy weeds	0.035	0.050	0.070
2. light brush and trees, in winter	0.035	0.050	0.060
3. light brush and trees, in summer	0.040	0.060	0.080
4. medium to dense brush, in winter	0.045	0.070	0.110
5. medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. dense willows, summer, straight	0.110	0.150	0.200

Manning's n for Channels (Chow, 1959), continuation

2. cleared land with tree stumps, no sprouts	0.030	0.040	0.050
3. same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. same as 4. with flood stage reaching branches	0.100	0.120	0.160
4. Excavated or Dredged Channels			
a. Earth, straight, and uniform			
1. clean, recently completed	0.016	0.018	0.020
2. clean, after weathering	0.018	0.022	0.025
3. gravel, uniform section, clean	0.022	0.025	0.030
4. with short grass, few weeds	0.022	0.027	0.033
b. Earth winding and sluggish			
1. no vegetation	0.023	0.025	0.030
2. grass, some weeds	0.025	0.030	0.033
3. dense weeds or aquatic plants in deep channels	0.030	0.035	0.040
4. earth bottom and rubble sides	0.028	0.030	0.035
5. stony bottom and weedy banks	0.025	0.035	0.040
6. cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline-excavated or dredged			
1. no vegetation	0.025	0.028	0.033
2. light brush on banks	0.035	0.050	0.060
d. Rock cuts			
1. smooth and uniform	0.025	0.035	0.040
2. jagged and irregular	0.035	0.040	0.050
e. Channels not maintained, weeds and brush uncut			
1. dense weeds, high as flow depth	0.050	0.080	0.120
2. clean bottom, brush on sides	0.040	0.050	0.080
3. same as above, highest stage of flow	0.045	0.070	0.110
4. dense brush, high stage	0.080	0.100	0.140
5. Lined or Constructed Channels			
a. Cement			
1. neat surface	0.010	0.011	0.013

Manning's n for Channels (Chow, 1959), continuation

2. mortar	0.011	0.013	0.015
b. Wood			
1. planed, untreated	0.010	0.012	0.014
2. planed, creosoted	0.011	0.012	0.015
3. unplanned	0.011	0.013	0.015
4. plank with battens	0.012	0.015	0.018
5. lined with roofing paper	0.010	0.014	0.017
c. Concrete			
1. trowel finish	0.011	0.013	0.015
2. float finish	0.013	0.015	0.016
3. finished, with gravel on bottom	0.015	0.017	0.020
4. unfinished	0.014	0.017	0.020
5. gunite, good section	0.016	0.019	0.023
6. gunite, wavy section	0.018	0.022	0.025
7. on good excavated rock	0.017	0.020	
8. on irregular excavated rock	0.022	0.027	
d. Concrete bottom float finish with sides of:			
1. dressed stone in mortar	0.015	0.017	0.020
2. random stone in mortar	0.017	0.020	0.024
3. cement rubble masonry, plastered	0.016	0.020	0.024
4. cement rubble masonry	0.020	0.025	0.030
5. dry rubble or riprap	0.020	0.030	0.035
e. Gravel bottom with sides of:			
1. formed concrete	0.017	0.020	0.025
2. random stone mortar	0.020	0.023	0.026
3. dry rubble or riprap	0.023	0.033	0.036
f. Brick			
1. glazed	0.011	0.013	0.015
2. in cement mortar	0.012	0.015	0.018
g. Masonry			
1. cemented rubble	0.017	0.025	0.030
2. dry rubble	0.023	0.032	0.035
h. Dressed ashlar/stone paving	0.013	0.015	0.017

Manning's n for Channels (Chow, 1959), continuation

i. Asphalt			
1. smooth	0.013	0.013	
2. rough	0.016	0.016	
j. Vegetal lining	0.030		0.500

Manning's n for Closed Conduits Flowing Partly Full (Chow, 1959)

Type of Conduit and Description	Minimum	Normal	Maximum
1. Brass, smooth:	0.009	0.010	0.013
2. Steel:			
Lock bar and welded	0.010	0.012	0.014
Riveted and spiral	0.013	0.016	0.017
3. Cast Iron:			
Coated	0.010	0.013	0.014
Uncoated	0.011	0.014	0.016
4. Wrought Iron:			
Black	0.012	0.014	0.015
Galvanized	0.013	0.016	0.017
5. Corrugated Metal:			
Sub drain	0.017	0.019	0.021
Storm drain	0.021	0.024	0.030
6. Cement:			
Neat Surface	0.010	0.011	0.013
Mortar	0.011	0.013	0.015
7. Concrete:			
Culvert, straight and free of debris	0.010	0.011	0.013
Culvert with bends, connections, and some debris	0.011	0.013	0.014
Finished	0.011	0.012	0.014
Sewer with manholes, inlet, etc., straight	0.013	0.015	0.017
Unfinished, steel form	0.012	0.013	0.014
Unfinished, smooth wood form	0.012	0.014	0.016
Unfinished, rough wood form	0.015	0.017	0.020
8. Wood:			
Stave	0.010	0.012	0.014
Laminated, treated	0.015	0.017	0.020
9. Clay:			
Common drainage tile	0.011	0.013	0.017
Vitrified sewer	0.011	0.014	0.017
Vitrified sewer with manholes, inlet, etc.	0.013	0.015	0.017
Vitrified Sub drain with open joint	0.014	0.016	0.018
10. Brickwork:			
Glazed	0.011	0.013	0.015
Lined with cement mortar	0.012	0.015	0.017
Sanitary sewers coated with sewage slime with bends and connections	0.012	0.013	0.016
Paved invert, sewer, smooth bottom	0.016	0.019	0.020
Rubble masonry, cemented	0.018	0.025	0.030

APPENDIX C: Base values of Manning's n

Table 1. Base Values of Manning's *n*

		Base *n* Value	
Bed Material	Median Size of bed material (in millimeters)	Straight Uniform Channel[1]	Smooth Channel[2]
Sand Channels			
Sand[3]	0.2	0.012	--
	.3	.017	--
	.4	.020	--
	.5	.022	--
	.6	.023	--
	.8	.025	--
	1.0	.026	--
Stable Channels and Flood Plains			
Concrete	--	0.012-0.018	0.011
Rock Cut	--	--	.025
Firm Soil	--	0.025-0.032	.020
Coarse Sand	1-2	0.026-0.035	--
Fine Gravel	--	--	.024

Table 2 . Adjustment Values for Factors that Affect the Roughness of a Channel [modified from Aldridge and Garrett, 1973, Table 2]

Channel Conditions	*n* Value Adjustment[1]	Example
Degree of Irregularity (n_1)		
Smooth	0.000	Compares to the smoothest channel attainable in a given bed material.
Minor	0.001-0.005	Compares to carefully degraded channels in good condition but having slightly eroded or scoured side slopes.
Moderate	0.006-0.010	Compares to dredged channels having moderate to considerable bed roughness and moderately sloughed or eroded side slopes. s in rock.
Severe	0.011-0.020	Badly sloughed or scalloped banks of natural streams; badly eroded or sloughed sides of canals or drainage channels; unshaped, jagged, and irregular surfaces of channel

Variation in channel cross section (n_2)

Channel Conditions	*n* Value Adjustment[1]	Example
Gradual	0.000	Size and shape of channel cross sections change gradually.
Alternating occasionally	0.001-0.005	Large and small cross sections alternate occasionally, or the main flow occasionally shifts from side to side owing to changes in cross-sectional shape.
Alternating frequently	0.010-0.015	Large and small cross sections alternate frequently, or the main flow frequently shifts from side to side owing to changes in cross-sectional shape.

APPENDIX D: Tide height profile.

Position reference sensor (prs) is a sea level monitoring type of sensor which provides information which allows the tide gauge measurement to be translated into Height at sea level relative to a Reference Datum (fixed ground – based level that compares the Global Positioning System, GPS position to the known position of the station, Differential GPS). The Kilindini Harbour Mombasa, and Lamu Tide Gauges employed shown in Figure 1D.

a)

b)

Figure 1D: a) Kilindini Harbour Mombasa and b) Lamu Tide Gauges respectively

The tide height is with reference to the prs (m) dimensions, and the graphs are drawn:
Tide height Vs time of the days (Date) shown. The transverse displacements of particles are governed by:

$$y = A\ \sin(kx - \omega t + \alpha)\ \text{m}$$

The transverse particle speeds are given by:

$$\frac{dy}{dt} = -\omega A \cos(kx - \omega t + \alpha)\ \text{m}$$

$$V_{max} = \omega A$$

In both sites we experience Semi-diurnal wave (Two high tides and two low tides per day). The combined 30-day wave constitutes two spring and two neap tides.

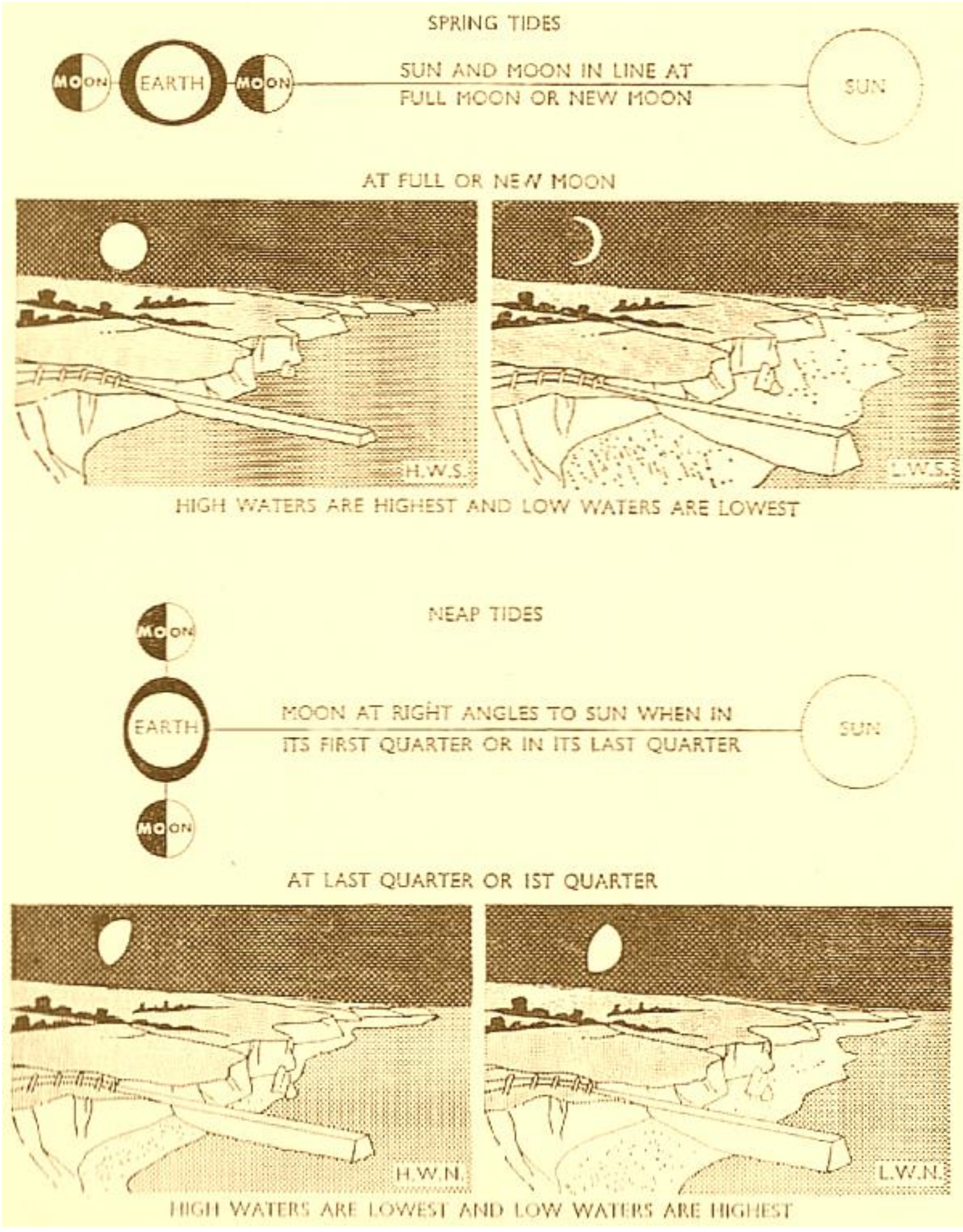

Figure 2D: Astronomy versus Spring and Neap Tides

APPENDIX E : Conference and Publications

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Estimating Marine Tidal Power Potential in Kenya

Authors : Lucy Patricia Onundo, Wilfred Njoroge Mwema

Abstract : The rapidly diminishing fossil fuel reserves, their exorbitant cost and the increasingly apparent negative effect fossil fuels to climate changes is a wake-up call to explore renewable energy. Wind, bio-fuel and solar power have alrea become staples of Kenyan electricity mix. The potential of electric power generation from marine tidal currents is enormo with oceans covering more than 70% of the earth. However, attempts to harness marine tidal energy in Kenya, has yet to studied thoroughly due to its promising, cyclic, reliable and predictable nature and the vast energy contained within it. T high load factors resulting from the fluid properties and the predictable resource characteristics make marine curre particularly attractive for power generation and advantageous when compared to others. Global-level resource assessme and oceanographic literature and data have been compiled in an analysis of the technology-specific requirements for ti energy technologies and the physical resources. Temporal variations in resource intensity as well as the differences betwe small-scale applications are considered.

Keywords : tidal power, renewable energy, energy assessment, Kenya
Conference Title : ICEE 2015 : 17th International Conference on Electrical Engineering
Conference Location : Montreal, Canada
Conference Dates : May 11-12, 2015

Assessment of Tidal Current Energy Potential at LAMU and Mombasa in Kenya

Authors : Lucy Patricia Onundo, Wilfred Njoroge Mwema

Abstract : The tidal power potential available for electricity generation from Mombasa and Lamu sites in Kenya will be examined. Several African countries in the Western Indian Ocean endure insufficiencies in the power sector, including both generation and distribution. One important step towards increasing energy security and availability is to intensify the use of renewable energy sources. The access to cost-efficient hydropower is low in Mombasa and Lamu hence Ocean energy will play an important role. Global-Level resource assessments and oceanographic literature and data have been compiled in an analysis between technology-specific requirements for ocean energy technologies (salinity, tide, tidal current, wave, Ocean thermal energy conversion, wind and solar) and the physical resources in Lamu and Mombasa. The potential for tide and tidal current power is more restricted but may be of interest at some locations. The theoretical maximum power produced over a tidal cycle is determined by the product of the forcing tide and the undisturbed volumetric flow-rate. The extraction of the maximum power reduces the flow-rate, but a significant portion of the maximum power can be extracted with little change to the tidal dynamics. Two-dimensional finite-element, numerical simulations designed and developed agree with the theory. Temporal variations in resource intensity, as well as the differences between small-scale and large-scale applications, are considered.

Keywords : energy assessment, marine tidal power, renewable energy, tidal dynamics
Conference Title : ICECSE 2015 : 17th International Conference on Electrical and Computer Systems Engineering
Conference Location : Montreal, Canada
Conference Dates : May 11-12, 2015

CERTIFICATE OF PRESENTATION

This certificate is awarded to

LUCY PATRICIA ONUNDO

in oral and technical presentation, recognition and appreciation of research contributions to ICEE 2015 : 17th International Conference on Electrical Engineering

Estimating Marine Tidal Power Potential in Kenya

Lucy Patricia Onundo

INTERNATIONAL SCIENTIFIC RESEARCH AND EXPERIMENTAL DEVELOPMENT

MONTREAL, CANADA

Authorized Signature

MAY 11-12, 2015

Kiel, 24.10.2016

Letter of invitation

Dear colleague,

Thank you very much for your interest in integrative ocean research and for applying for participation in our planned workshop. We would hereby like to invite you to the **"Scoping Workshop on the Development of an Integrative Ocean Research Network"**, taking place on **4-5 December 2016** at the Cruise Terminal Ostseekai in Kiel, Germany. The workshop will be jointly hosted by Future Earth, Future Ocean – Kiel Marine Science, ICSU, IOC, SCOR and WCRP.

The primary objective of the workshop is to discuss opportunities for international transdisciplinary marine research and activities that could be pursued by an integrative ocean research network over the coming years. For this purpose, we are gathering representatives from a range of academic and practitioner communities dealing with ocean sustainability, to discuss ideas, practicalities, and expectations, and co-design new activities together. Further information on the workshop can be found under here.

In the sign-up form you indicated that you are not able to self-finance your trip to Kiel. We would like to offer to cover your airfare (return ticket) and your hotel costs including breakfast for three days (3-6 Dec 2016). Lunches and dinner during the workshop will be provided. Please let us know if this is acceptable for you.

To confirm your participation please create an account and register. **Registration will close on the 27 October 2016**.

- You will have the possibility to present a poster at the **poster session** on the 4th of December. The content of the posters should be relevant to the objectives of the workshop, such as examples of knowledge-to-action case studies or studies related to oceans sustainability.

- We further encourage you to actively participate in shaping the contents of the workshop by proposing ideas on a specific research topic for integrative ocean sustainability research. If included in the programme, you will be offered to take the lead in a respective break-out groups during the **break-out group session** on 5 December.

Please submit your abstracts by the 20 November 2016.

We look forward to seeing you in Kiel!
Best regards,

The Workshop Committee:
Wendy Broadgate,
Charles Ebikeme,
Thorsten Kiefer,
Peter Liss,
Nora Papp,
Anke Schneider,
Craig Starger,
Josh Tewksbury, and
Martin Visbeck.

KIEL, GERMANY WORKSHOP REPORT

Attention:
Prof. Laila Abubakar, Vice Chancellor Technical University of Mombasa
Prof. Absaloms Heywood Ouma, Chairman Department of Electrical and Information Engineering University of Nairobi
Dr. Mika Odido, Kenya - IOC Coordinator in Africa at Intergovernmental Oceanographic Commission of UNESCO
Prof. Meoli Kashorda, Kenya Education Network KENET, the National Research and Education of Kenya providing a broadband platform for universities and research institutes
Dr. Wilfred Njoroge Mwema & Dr. Cyrus Wekesa Wabuge, University of Nairobi Supervisors
Prof. Saeed Mutta Mwaguni, Director Institute of research, innovation and extension TUM

The workshop on the Development of an Integrative Ocean Research Network (Future Earth "Oceans KAN) which I attended was held at the Cruise Terminal Ostseekai in Kiel, Germany on 4 - 5 December, 2016.

The primary aims of the workshop were:

1) to assemble representatives from several existing academic and practitioner communities dealing with ocean sustainability to co-design priority research activities

2) to discuss core ideas, practicalities, and expectations for an integrative ocean research network, including a synthesis of outcomes of recent, related workshops

3) to create a Development Team for the Ocean Research Network, set roles and responsibilities, and

4) to identify prospective partners (including non-academic, action-oriented groups) and possible funding institutions

Financial sponsors:

future ocean KIEL MARINE SCIENCES — Future Ocean - Kiel Marine Science

futurearth research for global sustainability — Future Earth - Research for Global Sustainability

INTERNATIONAL COUNCIL FOR SCIENCE — International Council for Science (ICSU)

सी एस आई आर - राष्ट्रीय समुद्र विज्ञान संस्थान

दोना पौला ४०३ ००४, गोवा, भारत

CSIR - National Institute of Oceanography

Dona Paula 403 004, Goa, India

CERTIFICATE

This certificate is awarded to Lucy Patricia Onundo

for having participated in the "Dynamics of the Indian Ocean: Perspective and Retrospective" International Symposium on the Indian Ocean organized at National Institute of Oceanography, Goa, India, during 30 November - 4 December, 2015.

Date: 04 December, 2015

Registration Committee
Chairman

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION
COMMISSION OCÉANOGRAPHIQUE INTERGOUVERNEMENTALE
COMISIÓN OCEANOGRÁFICA INTERGUBERNAMENTAL
МЕЖПРАВИТЕЛЬСТВЕННАЯ ОКЕАНОГРАФИЧЕСКАЯ КОМИССИЯ
اللجنة الدولية الحكومية لعلوم المحيطات
政府间海洋学委员会

UNESCO

IOC Sub Commission for Africa and the Adjacent Island States
UNESCO Regional Office for Eastern Africa, UN Gigiri Complex Block C
P.O. Box 30592 00100 Nairobi, Kenya
Phone: +254 (0) 20 7621244 – Fax: +254 (0) 20 7622750 – email: m.odido@unesco.org

Ref : IOCAFRICA/03-033 Nairobi, 27 March 2015

Dear Patricia Lucy Onundo,

Subject: Participation in meetings of the IOC Sub-Commission for Africa and Adjacent Island States - IOCAFRICA, Nairobi, Kenya 9-13 April 2015.

I have the honour to invite you to attend the following meetings organised by the IOC Sub-Commission for Africa & the Adjacent Island States in Nairobi, Kenya as an observer:

(i) 9-10 April 2015: Sino-Africa Forum on Marine Science and Technology

(ii) 11 and 13 April 2015: Forum on the Fuure of Sustained Ocean Observations in IOC Group 5 (Africa and Arab countries)

Further information and documents will be circulated shortly in the next few days.

We look forward to your particpation in the meetings.

Yours sincerely,

Mika Odido
IOC Coordinator in Africa.

Patricia Lucy Onundo
Department of Electrical and Information Engineering
University of Nairobi
Nairobi, Kenya
Email: patricialucyonundo@yahoo.com

NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY AND INNOVATION

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9th Floor, Utalii House
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P.O. Box 30623-00100
NAIROBI-KENYA

Ref: No. **NACOSTI/ADM/079**

Date: **6th May 2015**

Patricia Lucy Onundo
University of Nairobi

INVITATION FOR A POSTER PAPER PRESENTATION DURING THE 4TH NATIONAL SCIENCE, TECHNOLOGY AND INNOVATION WEEK, 11TH - 15TH MAY 2015

The Ministry of Education, Science and Technology (MOEST) and the National Commission for Science, Technology and Innovation (NACOSTI) are spearheading activities aimed at ensuring there is harmony in the identification and prioritization of Science, Technology and Innovation (ST&I) Policy and the implementation of programmes and projects in key sectoral areas. Pursuant to this, MOEST, NACOSTI and other partners have organized the 4thNational Science, Technology and Innovation (ST&I) Week to be held on 11th to 15th May 2015. The theme of the 4th National ST&I Week is: ***"The Role of Science, Technology and Innovation in the Post - 2015 Development Agenda"***. The major thrust of the Week will focus on: Agriculture and Food Security; Energy and Climate Change; Environmental Sustainability and Biological Resource Conservation; Water, Sanitation and Health; and Knowledge Management and Technology Transfer.

The objectives of the 4th National ST&I Week are to:

1) Raise public awareness and popularize science, technology and innovation among the citizenry;
2) Document Kenya's achievements and breakthroughs in the application of ST&I for the country's socio-economic growth and development;
3) Showcase, celebrate, recognize and reward outstanding Kenyan scientists and innovators; and
4) Articulate the Government's policies on research and ST&I

The event will be held at the Chancellor's Court, University of Nairobi. It will comprise keynote speeches for plenary sessions, case studies, roundtable discussions and exhibition of inventions and innovations based on thematic areas for the 4th ST&I Week.

Individuals, public and private institutions involved in training, research and policy will present papers and exhibits on ST&I. A Robotic Contest will also be held.

Participants will include policy makers, parliamentarians, academicians, scientists, development partners, civil society, the private sector and innovators.

The purpose of this letter is to inform you that your paper was among the few ones selected for poster presentation during this important occasion which would be held on 11th to 15th May, 2015; and also to request the Head/ CEO of your institution to approve and sponsor your participation during the event.

We look forward to your participation.

DR. M. K. RUGUTT, PhD, HSC
DIRECTOR - GENERAL/ CEO

NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY AND INNOVATION

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2241349, 3310571, 2219420
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Website: www.nacosti.go.ke
When replying please quote

9th Floor, Utalii House
Uhuru Highway
P.O. Box 30623-00100
NAIROBI-KENYA

Ref: No.
NACOSTI/RCD/ST&I/7TH CALL/MSc/154

Date: **25th April 2016**

Odundo Lucy Patricia
University of Nairobi
P.o. Box 30197-00100
NAIROBI

RE: SCIENCE, TECHNOLOGY AND INNOVATION RESEARCH GRANT (MSc/MA)

I'm pleased to inform you that National Commission for Science, Technology and Innovation (NACOSTI) has awarded you a research grant for your **MSc/MA research proposal**.

The NACOSTI has approved an amount of Kenya shillings ***One Hundred and Fifty Thousands Only (Kshs 150,000)*** towards your project titled ***"Estimating tidal energy potential along Kenyan coastline"*** Your awarded grant will be disbursed in one instalment.

Find the enclosed ***Research Grant Contract Form (NACOSTI/ST&I/CONTRACT/FORM 1C)*** that should be duly completed. In the contract form, provide clearly itemized yearly budget in the format provided and attach grant acceptance letter if you take up the offer.

Your duly signed contract form and acceptance letter should be sent back to reach us not later than **6th May 2016** for our further actions.

DR. MOSES K. RUGUTT, PhD, HSC.
DIRECTOR GENERAL

cc: Vice Chancellor,
University of Nairobi

IEEE

CERTIFICATE OF PARTICIPATION

This is to certify that

Patricia Lucy Onundo

Participated in the following:

IEEE Virtual Event on Energy-Efficient Communications and Communications Technologies

14 JANUARY 2016

Vice President, IEEE Educational Activities Board

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.
FOUNDED
NEW YORK
1884

Special Mention

Category: Technical Prefeasibility Study

Energise - Edulink Training July 2016 – Nairobi

The ENERGISE consortium formally recognized that Lucy Patricia Onundo

Was an active member of the team winning the project work competition on

"Call for CONCEPT NOTE: promoting renewable energy electrification in Kenya"

Prof. Emanuela Colombo,

UNESCO Chair in Energy for Sustainable Development,

Department of Energy, Politecnico di Milano

Scientific Coordinator ENERSGISE project

United Nations Educational, Scientific and Cultural Organization · UNESCO Chair in Energy for Sustainable Development

EDULINK

ENERGISE

KSEEE 0024

KSEEE

Kenya Society of Electrical & Electronic Engineers

JSAEM

Japan Society of Applied Electromagnetics and Mechanics

TECHNICAL UNIVERSITY OF MOMBASA

Certificate of Participation

This is to Certify that

Patricia L. Onundo

Successfully participated in the Kenya Society of Electrical and Electronic Engineers (KSEEE) 2014. International Engineering Conference held on 10th - 12th September 2014 at Technical University of Mombasa and Presented a paper entitled

'Solution to Economic Load Dispatch Using Particle Swarm Optimization (PSO) '

Conference Theme

Engineering Technology, Innovation and Entrepreneurship for a Green Economy

Prof. J.K.Z. Mwatelah
Vice Chancellor, Technical University of Mombasa

Prof. J.N. Nderu
Chair KSEEE Governing Council