UNIVERSITY OF NAIROBI

MODELING DAILY WIND SPEED AND DIRECTION USING HARMONIC ANALYSIS FOR THE DESIGN OF SEAWATER GREENHOUSE PROTOTYPE, IN KADZUHONI KILIFI COUNTY, KENYA

By

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DECLARATION

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

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DEDICATION

To my mother Mishi Salim Hussein and my children Mishi, Zainab, Salim, and Kauthar.

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ABSTRACT

The seawater greenhouse technology utilizes the radiation from the sun, seawater, humidity, wind speed and direction, and temperature to produce freshwater and cooled air in addition to providing the water for hydroponic section, supplying more sustainable environmental conditions for the cultivation of crops in arid and semi-arid coastal locations. The objective of the study was to examine the wind speed and its direction in the proposed Kadzuhoni area of Kilifi County for the design of a seawater greenhouse prototype, as well as to model wind speed and direction for the appropriate orientation of the seawater greenhouse prototype. Time series of wind speed and direction data were collected from the Kenya Meteorological Department (KMD) from 1st January 2021 to 31st December 2021. Statistical analysis was undertaken to model the wind speed and direction as well as perform the harmonic analysis model. The results showed that the wind speed in Kilifi County at Kadzuhoni proposed area for the seawater greenhouse prototype setup was found to vary with months. The general high wind speed recorded was 14 m/s and it was between May- June, and July – August, while the minimum wind speed was 2m/s and was found to be between December and January. For the East-West wind speed, it was observed that the maximum wind speed which was 11.22 m/s and blew from the East to the West, while the minimum wind speed was 10.79 m/s and blew from West to East. For the South-North wind speed, the maximum wind speed was 13.47 m/s and blew from the South to the North, while the minimum wind speed was 11.35 m/s and blew from North to South. In general, the calm wind has a frequency distribution of 11.8%, the speed 2.10 - 3.60 m/s has a frequency distribution of 4.9%, the speed 3.60 - 5.70 m/s has a frequency distribution of 12.3%, the speed 5.70 - 8.80 m/s has a frequency distribution of 25.3%, the speed 8.80-11.1 m/s has a frequency distribution of 14.8%, while the speed above 11.1 m/s has a frequency distribution of 30.8%. The harmonic analysis results of the model for observed and predicted were used to validate the model, by using the observed, predicted, and residual wind speed. It was found that there was no significant difference between the observed and the predicted values which characterized the model used as a good model. Since the southerly winds dominated with maximum speed of 13.47m/s, it is therefore recommended that the orientation of the seawater greenhouse, specifically the front evaporative pad, face the direction with the dominant wind speed for optimum collection of hot dry wind, and for cooling purposes. Therefore, these results will assist in setting up the seawater greenhouse prototype in Kadzuhoni proposed area without the use of fans.

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LIST OF ABBREVIATIONS AND ACRONYMS

ASAL	Arid and Semi-Arid Lands
ARMA	Auto Regressive Moving Average
ECSSR	Emirates Centre for Strategic Studies and Research
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
KMFRI	Kenya Marine and Fisheries Research Institute
KMD	Kenya Meteorological Department
m	Meter
NEM	Northeast Monsoon
SEM	Southeast Monsoon
SWGH	Sea Water Green-House
UAE	United Arab Emirates
UK	United Kingdom
u	West-East Direction of wind component
v	North-South Direction of wind component
ws	Wind speed
θ	Direction angle measured in degrees

CHAPTER ONE: INTRODUCTION

1.0 Background of the Study

The seawater greenhouse technology utilizes the radiation from the sun, seawater, humidity, wind speed and direction for cooling purposes, temperature, and other structural parameters to produce freshwater and cooled air in addition to providing the water for the hydroponic section, supplying more sustainable environmental conditions for growing of crops in arid and semi-arid coastal locations. The idea of its operation depends on the climatic conditions of the region to create a natural water cycle in a controlled environment. The main purpose of the seawater greenhouse is to provide sustainable farming in dry coastal areas where there is shortage of fresh water and the cost of desalination impend the feasibility of farming.(Paton and Davies, 2006). The flow of fluids such as humidity/water vapor, into the seawater greenhouse, as well as cooling of the water vapor, depend highly on the wind speed and direction.

Initially, the Seawater Greenhouse prototype was set up in 1994, in the south of Tenerife, near Granadilla in Spain. The crops cultivated in the prototype included spinach, French beans, tomato, artichokes, dwarf pea, pepper, and lettuces (Davies *et al*., 2004). The Greenhouse was designed in such a way that its front wall faced the prevailing wind where it continuously became wetted with seawater vapor due to its porous structure. The outcome of the dry wind coming into contact with this large wet evaporative pad was substantial to generate humidity and cooling effect, and produce about 1.5 m^3 of water per day.

Kenya is located in a hot tropical region affected by the strong winds of the Indian Ocean monsoons. The climate and meteorological system along the Kenyan coast in the western Indian Ocean consist of two main different monsoon seasons which are the northeast monsoon (NEM) from October to early March and the southeast monsoon (SEM) from March to October. During the NEM season, Kenya's weather, especially on the coast, is characterized by relatively dry weather. Winds blow in the east-southeast direction during the months of March and April, and strong sea air from the Indian Ocean causes heavy rain. In May, June, July, and August, the effects of the southeast monsoon begin slowly, with cloudy and relatively cold temperatures and more stable weather. The northeast monsoon gradually returns from September to November, and the effects of the north wind regain control in December. (Magori, 2009). Although Kenya has these variations patterns, still some parts are arid and semi-arid such as Kadzuhoni in Kilifi.

Many studies had shown that the performance of Seawater Greenhouse depends mainly on environmental conditions. They also showed that greenhouses thrive in stable, windy, hot, sunny, and dry coastal areas. (Zarei and Behyad, 2019b), Kilifi County has these same weather characteristics.

1.1 Working Mechanism of The Seawater Greenhouse

Below is a description of the various stages of the working mechanism of the seawater greenhouse (See Figure 1)

1) On the main stage, the inflowing air (wind) flows through the first porous evaporative pad and comes into contact with the droplets of seawater at a lower temperature than that of the outside.
2) After passing through the first porous evaporative pad, the heat exchange with seawater lowers the temperature of the air.
3) This cold, moist air enters the greenhouse. Greenhouse warms the air day and night, creating a moderate climate for plants to grow. This air is not extremely hot and less sticky, so it is less steamy.
4) The seawater that leaves the first porous evaporative pad is sent into the seawater greenhouse as water vapor and get more heated by energy from the sun. The heated vapor is forced to flow by the wind to the second porous evaporative pad on the edge of the seawater greenhouse.
5) The air flowing through the seawater greenhouse when approaching the immersion point, it gets very wet. The total humidity of the heated air reaches one hundred percent and contains a lot of water vapor. The extreme stickiness of this exhaust from the second porous evaporative pad is a direct result of high temperatures.
6) This warm, sticky air can pass through the condenser in the next step to provide sufficient purified water through the wind-driven condensation instead of fans. Some of this water can be used for planting crops in the seawater greenhouse and the rest for drinking.

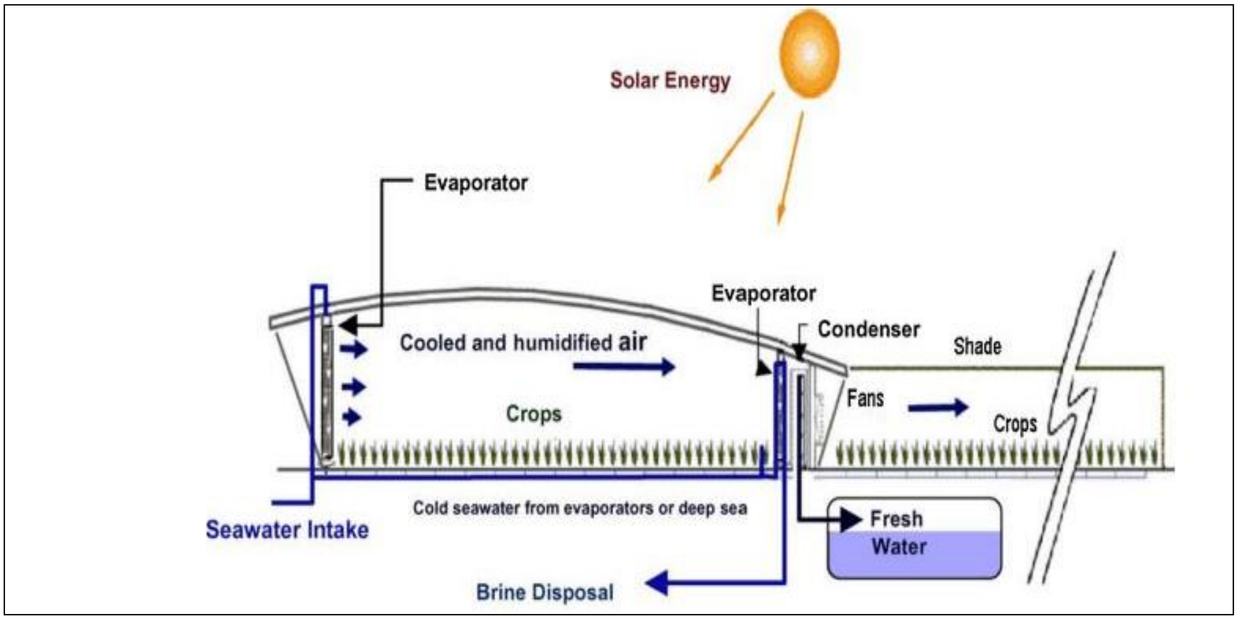

Figure 1: A picture of seawater greenhouse (Ahmed *et al*., 2003)

1.2 Problem Statement

Studies showed that parameters such as humidity, wind speed, and temperature are key in determining the amount of condensation (Zurigat *et al*., 2008). Passage of parameters such as water vapor into the seawater greenhouse mainly depends on the wind speed and direction. Wind acts as a cooling system in seawater greenhouse for condensation of water vapor.

Previous studies concentrated on the technical improvement of SWGH performance, hence came up with a number of adjustments to the current existing seawater greenhouse design in order to enhance its performance for freshwater production. However, it was observed from the previous studies that there is a knowledge gap in the economic aspects of seawater greenhouse due to the absence of research interest in this area. Many studies used fans as cooling mechanism which is very expensive to maintain especially for poor community based project, whereby this cost can be reduced by attaining a certain amount of wind speed(Davies *et al*., 2004), therefore this study was aim to model the daily wind speed and direction for the design of seawater greenhouse at Kadzuhoni Kilifi County, to reduce the capital costs of the fans

1.3 Justification

Kilifi County is classified as a poor region with a high rate of needy population facing sustenance and water insecurity. Large population in this region depends on agricultural activities such as farming, for their livelihood, but the main challenge is the rainfall scarcity. An occasional shortage of water exists in this region. Floods and dry seasons occur as often as possible, in this manner compromising efficiency and food security in the area (Nabwire, 2020).

Kilifi County, Kenya has experienced relentless water issues because of many variables like rapid population development, and high temperatures which cause dryness to the region(Kariuki, 2018).

The County is currently experiences low yield, increased frequencies of extreme weather events, and food insecurity (Ogega *et al*., 2020). This study will also assist the community to set up the seawater greenhouse at the right position and facing the right direction, and alleviate the impact of climate change by creating a good environment for crop growing.

Studies showed that seawater greenhouse can enhance agricultural activities by creating conducive environment for growing crops, however depending on its design chosen can be expensive, such as cost of running fans when using fans for cooling mechanism instead of using wind, but also for it to use only wind speed, the median wind speed must at least be 4m/s (Davies *et al*., 2004), therefore this study was aim to model the daily wind speed and direction for the design of seawater greenhouse at Kadzuhoni Kilifi County, to reduce the capital costs of the fans

1.4 Research questions

The following are the research questions for this study.

i. Where can be the relevant wind data be acquired from?
ii. What is the maximum wind speed in the proposed area?
iii. How is the wind speed and direction behaving in the proposed area?
iv. Which is the best orientation of the seawater greenhouse prototype?

1.5 Main Objective

The main objective of this study was to model the wind speed and direction in the proposed area of Kadzuhoni for the design of the seawater greenhouse prototype.

1.5.1 Specific Objectives

The specific objectives included the following:

i. To acquire relevant wind data and perform data quality control on the collected data
ii. To examine the maximum wind speed of the proposed area
iii. To examine the wind speed and direction in the proposed area of Kadzhuhoni.
iv. To determine the appropriate orientation of the seawater greenhouse set up

1.6 Study Area

The seawater greenhouse prototype will be set up at Kadzhuhoni area of Malindi in Kilifi County, at coordinates (2^0 52’26.74” S, 40^0 10’08.45” E), and (2^0 52’26.03” S, 40^0 10’04.66” E). The site is quite open with no obstructions to the wind flow and other climatic conditions. The setup will depend on the wind speed and direction for appropriate orientation and the penetration of hot dry winds from the sea as well as for cooling purposes. This works on the principle of evaporation and condensation, which efficiently replicates water cycles by evaporating seawater from the seawater greenhouse evaporative pad and condensing water vapor at relatively low temperatures inside the seawater greenhouse.

Kilifi county is a semi-arid and experiences frequent drought and irregular wet seasons(Comte *et al*., 2016). Figure 2 gives the location of the study area.

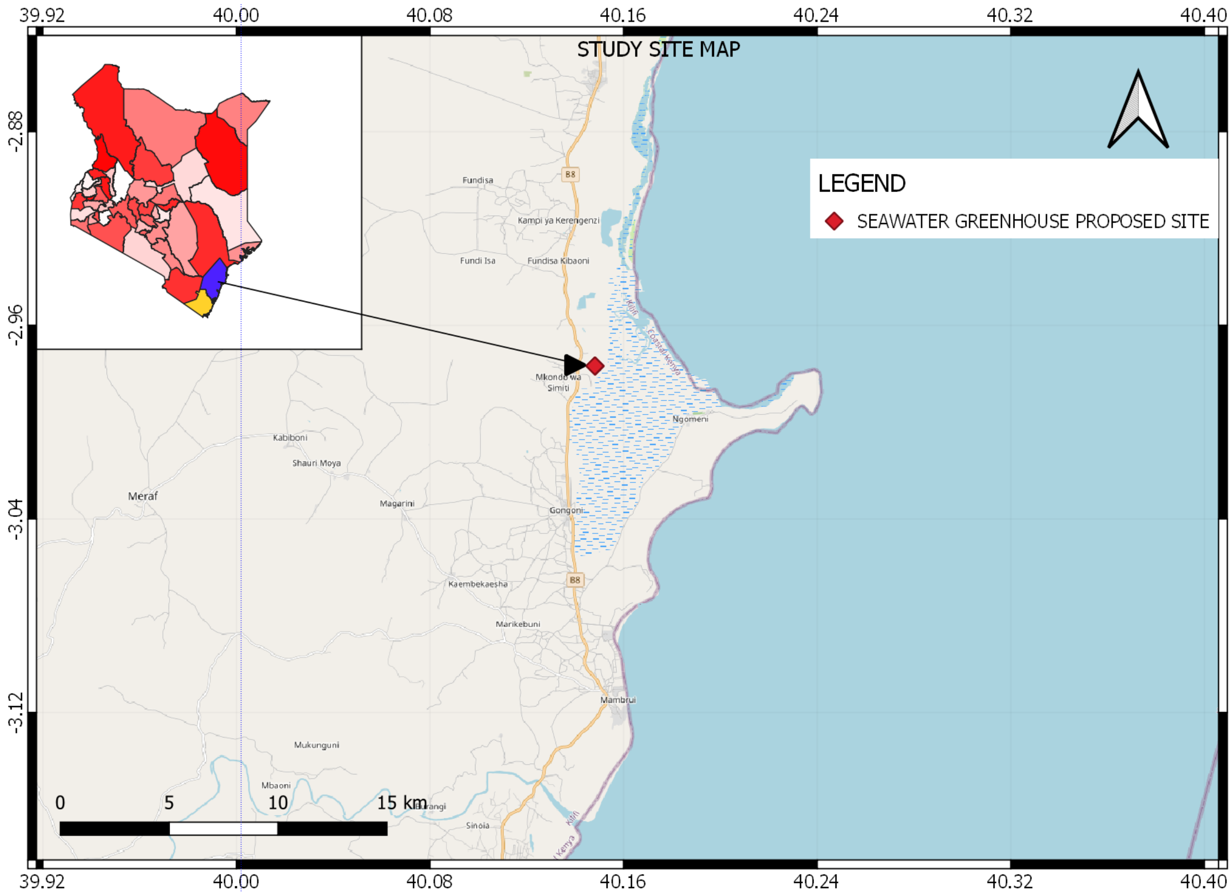

Figure 2: Map of the study area (Generated through QGIS on 19th April 2022)

1.6.1 Climate and weather systems in Kilifi County

Climate change is causing droughts due to the increase in average temperatures. Most of agriculture dependence countries are affected by these droughts. In Kenya, the coastal city of Kilifi experiences these droughts as well. Previous studies showed that the coastal wind in Kenya is associated with the monsoons wind systems (Francisco *et al*., 2018). Weather systems on the Kenyan coast consist of two main seasons, Northeast Monsoon (NEM), starting from October to early March, and Southeast Monsoon (SEM), starting from March to October. During the Southeast Monsoon the easterly winds off the Somali coast flow is overridden by a westerly flow towards the Asian continent.

During the NE monsoon the wind passes over the dry Somali land which consequently leads the coastal area like Kilifi to receive a small amount of rainfall (McClanahan, 1988).

The distinction between Northeast and Southeast monsoons is that they have two distinct coastal seasons, two wet seasons and two dry seasons. Southeast monsoon is characterized with decreased temperatures, high wind speed, cloud cover, and rain which is opposite to the characteristics of Southeast monsoon. These climatic phenomena ultimately affect the performance of Seawater Greenhouse (McClanahan, 1988).

Kenya's economic depends on agriculture and related sectors and all of these sectors predominantly depend on climate. In Kilifi about 90 percent of the community is practicing farming, and depends on rainfall for their agricultural activities as a primary source of their livelihood. Kilifi County has a mean annual rainfall of about 1300mm at the coastal strip and about 300 mm at the hinterland. The average temperature along the coast varies between 21^0C and 30^0C while that of the hinterland varies between 30^0C and 34^0C.

1.6.2 Factors influencing climate change over Kenya

Factors influencing climate change in Kenya including unsustainable human activities that had led to increased floods, heat stress, and drought frequency, such as deforestation(Pello *et al.*, 2021). Some studies have shown that there is an increasing scientific consensus that climate change is attributed to anthropogenic greenhouse gas (GHG) emissions (Ogega *et al*., 2020).

Kenya's climate is influenced by its nearness to the equator, the Intertropical Convergence Zone (ITCZ) and the Indian Ocean. The intensity of the ITCZ and seasonal variability governs the rainfall patterns of Kenya (Kogo *et al*., 2021).

There has been a global mean temperature rise over the last one hundred years in a linear trend of 0.74 ^{0}C (IPCC, 2007). According to the Intergovernmental Panel on Climate Change latest report, the global mean temperature rise is due to anthropogenic causes and is projected to reach 1.5 °C between 2030 and 2052 (IPCC, 2018).

1.6.3 Land Uses and Resources

The fundamental kinds of land uses are animal keeping especially livestock, developing dry season safe yields, fisheries, and sand harvesting. Farming is the super monetary action of individuals. Arable rural land is under limited scope crop creation with the primary food crops developed being maize, beans, and cassava (Mwangi, 2016).

1.6.4 Physiography and drainage

The area has got saltwater ponds for salt mining exercises that are being recharged by the Indian Ocean High tides, in addition to this, it also has dunes, mangroves, and scrubland. The saltwater ponds channel their water to the Indian Ocean during low tide (Ariana, 2016).

1.6.5 Water Resources

The fundamental wellspring of water in this area is River Sabaki, shallow wells inside the ridges, while on occasion individuals are compelled to go somewhere in the range of not many Kilometers from Sabaki towards Malindi to get water for utilization. The Sabaki River is Kenya's second-longest river with its waters beginning from the Aberdares, Ngong, and Mount Kenya in the upcountry and via Nairobi and Central locations of Kenya (Marete, 2006).

CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

The chapter gives a background of the seawater greenhouse and an overview of the research done on seawater greenhouse globally and locally. It also gives information on the existing knowledge on the seawater greenhouse from global and local perspectives.

2.1 Seawater greenhouse performance globally

The performance of seawater greenhouse depends mainly on solar radiation, temperature, wind speed and wind direction, and relative humidity. These parameters are constantly changing in relation to each other throughout the day and throughout the seasons. It is these changing climatic conditions that drive and affect the performance of the seawater Greenhouse. Consequently, small changes to the design can have a significant effect on its performance (Paton & Davies, 2006).

2.2 Seawater greenhouse performance in Spain

The first seawater greenhouse prototype was constructed in the south of Tenerife near Granadilla, in 1994. Here the seawater greenhouse main structure covered an area of about 360 m^2 and was completely planted with crops. The main crops that were cultivated in this prototype including spinach, tomato, dwarf pea, artichokes, pepper, lettuces, and French beans. Some areas around the Greenhouse were also irrigated allowing indigenous vegetation to be reestablished on that arid and windswept coast. The greenhouse was made to face into the prevailing wind and was ventilated by wind pressure alone, without the use of fans to avoid high cost (Davies & Paton, 2007)

The seawater greenhouse front wall that was facing to the prevailing wind being a porous was wetted with seawater continuously, and the results of the wind coming into contact with this moist surface were substantial to generate humidity and cooling effect inside the seawater greenhouse.
According to David *et al*., 2004 the wind pressure was sufficient enough to drive the air through the front wetted wall up to the second back wetted wall of the seawater greenhouse and finally through a tube-and-fin type condenser. The second evaporative pad at the back of the seawater

greenhouse condenser was fed with cold seawater which caused freshwater to condense on its surface. Water production was at the rate of 1.5 m^3 per day (Davies *et al*., 2004)

2.3 Seawater greenhouse performance in the UAE

The seawater greenhouse concept was established in December 2000, it was constructed in the United Arab Emirates (UAE) at Alaryam, which was as a result of a collaboration with the Emirates Centre for Strategic Studies and Research (ECSSR). The seawater greenhouse, covered an area of 864 m^2, and was producing crops year-round.

Some adjustments were done in order to increase the water production to reach 1 m^3 per day, which was sufficient enough to cater for the irrigation demand of the crops. Among the adjustment done was to add an array of tubes to provide solar heating to the seawater being fed into the back wall evaporative pad of the seawater greenhouse.

According to (Davies *et al*., 2004) it was indicated that the sites with a median wind speed value of 4 m/s would be sufficient enough to provide wind-driven ventilation to the seawater greenhouse without the use of fan, while those sites with lower median values such as 2m/s and below would have to incorporate fans for optimum performance of the seawater greenhouse.

2.4 Seawater greenhouse performance in Oman

The seawater greenhouse in Oman was assembled in the UK and transported to Oman in December 2003. The Construction in Oman started in January 2004 and was completed by the end of January by a team of four engineers from the UK together with locals' labor in Oman. Cooler and more humid conditions allowed crops to be grown even during the hottest summer months through the year. Remarkably, there was no required pesticides for the crops in the seawater greenhouse, compared to normal greenhouses where spray has to be done on the crops for whitefly during the growing seasons at least 7 times.

The scientific reasons for this difference in the greenhouses are not yet clear, although there is a hypothesis that the salt water evaporative pads had an air scrubbing effect due to the contact with the hot dry winds, such that any airborne insects or contaminants were washed out of the incoming ventilation air. Fans were used as cooling mechanisms in this Seawater Greenhouse so as to improve its performance as well as getting high yields all year round (Paton & Davies, 2006).

The use of fans instead of wind speed only made the Seawater Greenhouse to be costly in this area. This is why in this study it is intended to model the wind speed and direction in order to setup the Seawater Greenhouse and make it face to the direction of the prevailing wind speed, and reduce the cost of the fans.

2.5 Seawater greenhouse performance in Australia

The Australia project started in 2010 and marked the first venture with a commercial focus. The task started as a 2000m^2 pilot facility close to Port Augusta and presently, under new proprietors, Sun drop Farms had scaled up 100-fold to 20 hectares.

The essential key parameters of the greenhouse were electricity, heat, nutrients, and water. The Sun drop structure is an assortment of techniques that, when combined, reduce the need to utilize limited resources. It was the first technique used to combine power, heat, and water system powered by energy from the sun for seawater greenhouse production. The Sun drop farm was the first facility in South Australia, with these technologies incorporating thermal desalination, steam-driven electricity, and, concentrated solar power.

The Sun drop system includes the utilization of the energy from the sun to produce freshwater for land irrigation. The sun's energy was converted to electricity. Seawater was drawn from the Spenser inlet to evaporative cooling systems and to feed out the desalination plant, solar energy systems produced power, heat, and water along these lines reducing the dependence on petroleum derivatives. The Steam created from the Concentrated Solar Power was taken care of into a steam turbine to produce electricity. Desalination using heat and seawater was taken through a refining cycle process to produce fresh water.

The freshwater was enhanced with town water and nutrients and used to irrigate crops. It was noticed that the original pilot plant at Sun drop Farm desalinated seawater, but collected brine in a pond where salt could be extracted. Sun drop Farm has been approved by the South Australian

Environmental Protection Agency to dump 60/1000 salt waste into the Spencer Gulf. This type of seawater greenhouse was expensive to maintain (Al-Ismaili & Jayasuriya, 2016).

2.6 Seawater greenhouse performance in Somaliland

Somalia is certifiably not a solitary political element however includes a few political and ancestral locations, specifically, oneself proclaimed state of Somalia. As per (Milanović, 2021),
In the 1930s, Somalia was considered home to the world's largest salt works at Hafun, until when it was destroyed in the Second World War in 1941. Somali has arid climate, it has average temperatures of 29 °C between December and January, and average temperature of between 41–42 °C between July and August, and average low precipitation of about 50mm. These arid climatic conditions limit the productivity of agricultural produce to 0.5 tonnes/ha, and very few arable crops are cultivated under 1.8 percent of the land.

The main economic activity of the Somalia and Somaliland is livestock rearing which accounts for 40 percent of their GDP. Somalia initially had no desalination plants until when the UK Department for International Development sponsored a project under the innovate- UK Agri-Tech Catalyst Programme in order to promote agricultural productivity in Somalia using Seawater Greenhouse. The Seawater Greenhouse was incorporated with a desalination plant and a fun at the second evaporative pad for cooling purposes in order to produce water for irrigation (Akinaga *et al.*, 2018).

This system was expensive since it had economic implications to fuel, electricity bills, and other operational costs. These costs can be reduced by means of using only wind speed for cooling purposes.

2.7 Modelling daily wind speed using harmonic analysis for Marmara region in Turkey

A study that was done in Turkey at Marmara region indicated that different sites have different wind speed and direction measurements and can be analyzed using different methods such as time series analysis and statistical approach. However, the time series method is not applicable in case of irregularly scattered wind data in a given area. Furthermore, time series technique requires assumptions such as specific wind distribution, variance constancy, and linear dependence, which most of wind speed data do not satisfy all these assumptions (Sirdaş, 2005)

On the other side, researchers have seen harmonic analysis as the most suitable model for combining different sine and cosine waves of wind speed data (Şen, 1980). Other researchers who used harmonic analysis model including Baldasano and Berna (Şen, 1980) for modelling hourly solar irradiation in Spain. Harmonic analysis has also been used get variance for precipitation values in Turkey, as well as identification of rainfall regimes (Şahin *et al.*, 2001).

2.8 Analysis and modelling of time series of surface wind speed and direction in Barcelona, Spain

Studies have shown that time series analysis of wind speed and direction data have many application in many fields. Among the application is the understanding of atmospheric phenomena, as well as in the field of agriculture, estimation of solar and wind resource, and general global change studies. Modelling of the wind speed and direction can done using harmonic analysis, simple characterization of statistical distribution of wind data series, probabilistic process such as ARMA, differential model equations. Harmonic analysis has been used to model wind speed and direction in different studies to identify cyclic components as well as to identify the wind trend if any (Martín *et al.*, 1999). This is why it has been selected to be used in the modelling of wind speed and direction in Kadzuhoni Kilifi County to reduce the costs of running fans for cooling and evaporative purposes for seawater greenhouse prototype setup.

CHAPTER THREE: MATERIALS AND METHODS

3.0 Introduction

The study adopted the methods of harmonic analysis to model wind speed and direction in order to identify the cyclic and trend of the wind speed (Martín *et al*., 1999). Time series of wind speed data was analyzed using harmonic method to identify the trend, strength, as well as direction of the wind (Sirdaş, 2005). The reason for using this method for modelling the wind speed is because harmonic analysis was ranked as the most suitable model for combining different sine and cosine waves of wind speed data (Şen, 1980)

3.1 Data collection

To answer specific objective one, the relevant wind speed and direction data was obtained from the Kenya Meteorological Department (KMD) at Msabaha weather station which is approximately 30km from the study site. This was within the recommended distance of 50km (OLIMA, 2021). The data was for a period of one year, January 2021 to December 2021.

3.2 Data quality control

The wind speed data from the Kenya Meteorological Department passed through quality control by checking whether there was outlier. Consistency of the data was also checked to make sure that there was no variation in the data. The data also passed through data completeness check to make sure that there was no gaps or missing information, as well as uniqueness check so as to see whether was duplicated or overlapped.

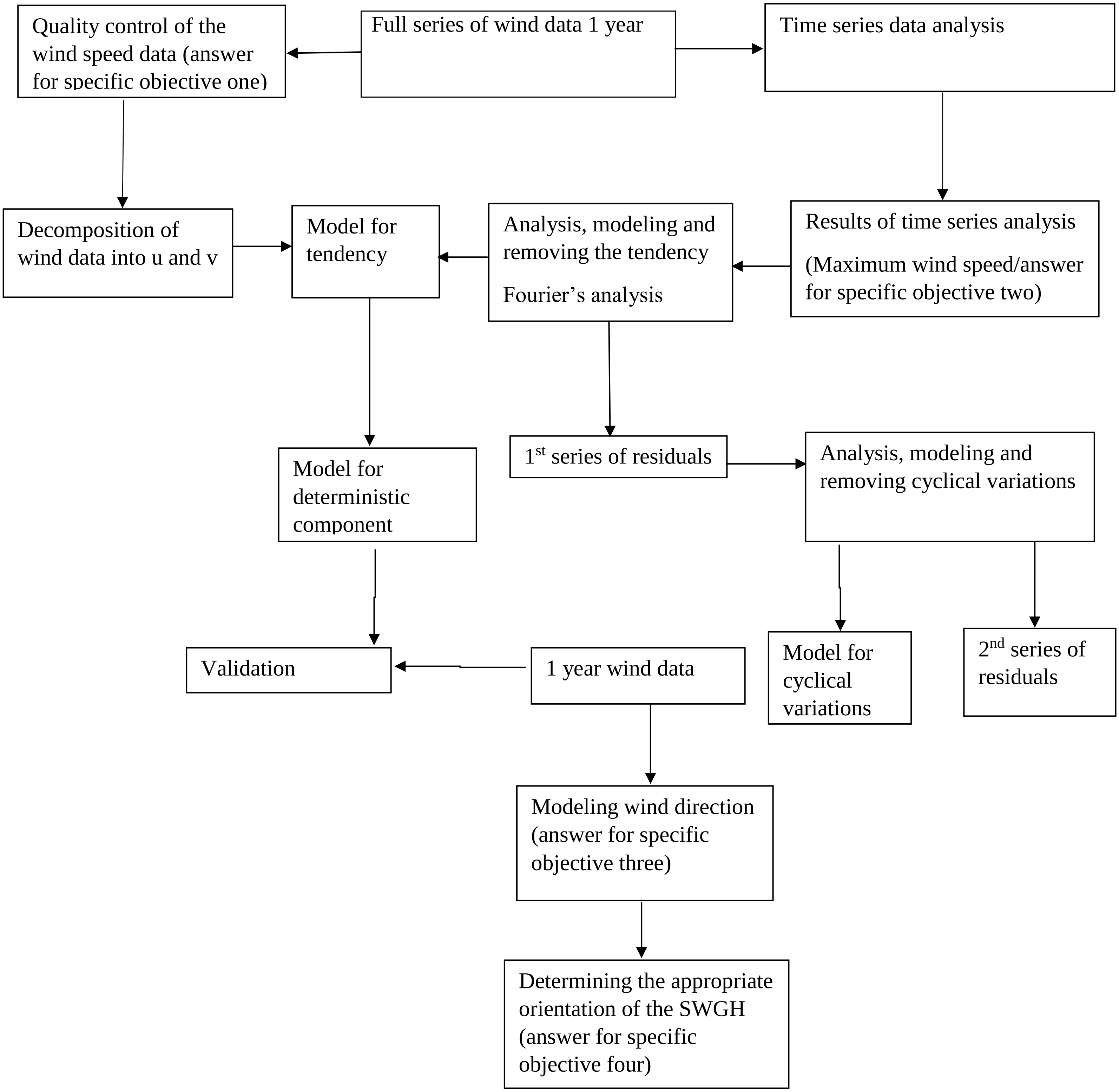

Figure 3: Harmonic analysis modeling of the wind speed and direction conceptual framework

3.3 Data Analysis

Time series harmonic analysis was used to model the wind speed and direction. The equations below were used: The west-east velocity component (u) and the north-south velocity component (v) for wind speed were determined using the following equations.

3.3.1 Decomposition of wind speed and direction

The west-east velocity component (u), and north-south velocity component (v), were determined using the equations below:

$$u = -ws * \cos(\theta) \quad \text{………………………………………………… (1)}$$

$$v = -ws * \sin(\theta) \quad \text{…………………………………………………. (2)}$$

Where ws is the wind speed recorded and θ is the direction angle measured in degrees.

3.3.2 Harmonic Analysis

Harmonic analysis is a numerical technique for separating sinusoidal parts of the explicit frequencies, for example, a record of wind speed and direction. In this case, it is based on the "least squares method". Instead of fitting a straight line to the information by shifting the slope and detecting it, we changed the amplitude and phase to fit a set of cosine or sine curves of a particular frequency and minimize the total deviation from the original curve.

Given a time series Z (t) of the data points, it can be represented as a combination of sine and cosine functions (Magori, 2009).

$$Z(t) = \sum_k a_k \sin(\omega_k t) + \sum_k b_k \cos(\omega_k t) \quad \text{…………………………………………(3)}$$

Where a_k and b_k represent the coefficients of the concerned harmonics, ω_k represents phase angle, and t represents time

The values of a_k and b_k can be determined for the given frequencies, ω_k by minimizing the sum of squares of the distinctions between the hypothesized function and the given time series Zn.

For least-squares fit, the following function should be minimized (Sirdaş, 2005).

$$f(a_k, b_k) = \sum_{n=1}^{N}\left(z_n - \sum_k a_k \sin(\omega_k t_n) + \sum_k b_k \cos(\omega_k t_n) \right)^2 \qquad \text{……………………………………(4)}$$

This requirement is met by

$$\frac{\partial f}{\partial a_i} = 0 \qquad i = 1,\ldots,k \qquad \text{…………………………………………………………………..(5)}$$

and

$$\frac{\partial f}{\partial b_i} = 0 \qquad i = 1,\ldots,k \qquad \text{………………………………………………………………………….(6)}$$

Where

$$\frac{\partial f}{\partial a_i} = -2\sum_{n=1}^{N} \cos(\omega_i t_n)\left(z_n - \sum_k a_k \sin(\omega_k t_n) - \sum_k b_k \cos(\omega_k t_n) \right) = 0 \qquad \text{…………………………………(7)}$$

and

$$\frac{\partial f}{\partial b_i} = -2\sum_{n=1}^{N} \sin(\omega_i t_n)\left(z_n - \sum_k a_k \sin(\omega_k t_n) - \sum_k b_k \cos(\omega_k t_n) \right) = 0 \qquad \text{……………} \qquad (8)$$

The above conditions can be revamped as follow:

$$\sum_k a_k \sum_{n=1}^{N} \sin(\omega_k t_n)\cos(\omega_k t_n) + \sum_k b_k \sum_{n=1}^{N} \sin(\omega_i t_n)\sin(\omega_k t_n) = \sum_{n=1}^{N} Z_n \sin(\omega_i t_n) \qquad \text{……………...(9)}$$

$$\sum_k a_k \sum_{n=1}^{N} \cos(\omega_k t_n)\cos(\omega_k t_n) + \sum_k b_k \sum_{n=1}^{N} \cos(\omega_i t_n)\sin(\omega_k t_n) = \sum_{n=1}^{N} Z_n \cos(\omega_i t_n) \qquad \text{…………} \quad (10)$$

3.4 Spectral Analysis

The spectral analysis which one of the most popular ways to analyze time-series data in the physical sciences is via spectral analysis, was also used in addition to the harmonic analysis in order to determine the prevailing wind speed frequencies. A linear mixture of sinusoids with varied frequencies and amplitudes was used to depict a time series. A Fourier transformation is a sort of representation that uses this technique.

Time series may be examined in the frequency domain using spectral plots, which can be shown on a graph. The autocovariance function has been smoothed using a Fourier transform to get the spectral plot. Before producing the spectral plot, trends in the time series should be erased. The spectral analysis is often used to the residuals to eliminate the trends. In the sinusoidal paradigm, a beginning value for the frequency (ω) may be found using spectral plots. To determine the "prevailing" frequency of the wind speed time series, we defined the power spectral density G (f) as: $G(f) = \frac{2}{T}|Y(f)|^2$ ………………. (14)

Where Y(f) is a discrete function and T is the period of the time series.

$$G(f) - \frac{2\Delta t}{N}|Y(f)|^2 \quad \text{………………} \quad (15)$$

N is the number of measurements used to indicate the strength spectral density. Analyzing G (f) helps you to identify the most important frequencies in a signal. This is most likely because it is a very essential frequency in physical processes (Magori, 2009). Period-gram estimation may be used to estimate the power spectrum as well as determine the prevailing frequencies of the wind speed.

3.5 Distribution functions

The goodness of fit to the wind speed data was evaluated using the t-Location-Scale and EpsilonSkew Normal distributions. In the theory of probability, especially in mathematical statistics, a t-location–scale family is a family of probability distributions that is parametrized by a location parameter and a non-negative scale parameter. For any random variable X whose probability distribution function belongs to such a family, the distribution function of Yd =a + bX also belongs to the family (where d means "equal in distribution"—that is, "has the same distribution as"). Here the t-Location-Scale distribution was chosen for the fit simply because the wind values are positive.

The Epsilon Skew-Normal distribution is a continuous probability distribution that generalizes the normal distribution to allow for non-zero skewness (Faezirad *et al.*, 2021). Here it was chosen for the fit because it seems to be closer to fit the data as well as t-Location distribution.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.0 Introduction

This chapter is about the findings from the study. The chapter contains the results from the model of the wind speed and direction for the design of seawater greenhouse prototype in Kadzuhoni Kilifi County.

4.1 Results from time series wind speed analysis

Figure 4 shows the time series of wind speed variation at Kadzuhoni between January2021 to December 2021. The wind speed in Kilifi County at Kadzuhoni proposed area for the seawater greenhouse prototype setup was found to vary with months. The maximum wind speeds recorded was 14 m/s between May- June, and July – August, while the minimum wind speeds were found between December and January. These results therefore answer specific objective two as it gives the maximum wind speed recorded from January 2021 to December 2021. These results imply that the maximum cooling effects of the inside seawater greenhouse will be between May – June and July – August.

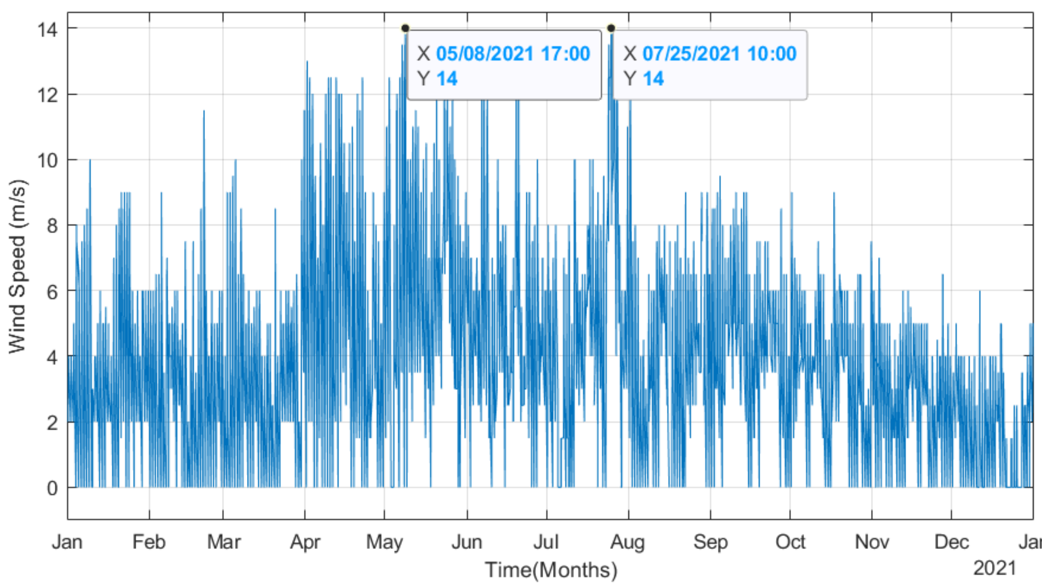

Figure 4: Time series of maximum wind speed recorded

4. 2 Model results from West-East wind Component speed (u)

Figure 5 below presents the variation of the model Wind Component (u) at Kadzuhoni area which is characterized by West-East wind flow. Wind speed data is always reported as the magnitude of the component vectors u and v. Negative component u means the wind, blew from West to East, and which is parallel to the x-axis (i.e. longitude). Positive component u means the wind blew from East to West. From Figure 4 it is evident that the wind that blew from East to West had a maximum wind speed of 11.22 m/s, which characterized easterly winds, while the maximum wind speed that blew from West to East was 10.79 m/s, which characterized westerly winds. According to the proposed site, the East side is the side where the Indian Ocean is located, as it is shown on the study site map, Figure 2. Therefore, this implies that the easterly winds will carry the hot dry air from the Indian Ocean to the seawater greenhouse's first evaporative pad. These results therefore answer specific objective three partially, as it gives the wind speed and direction of the West and East direction.

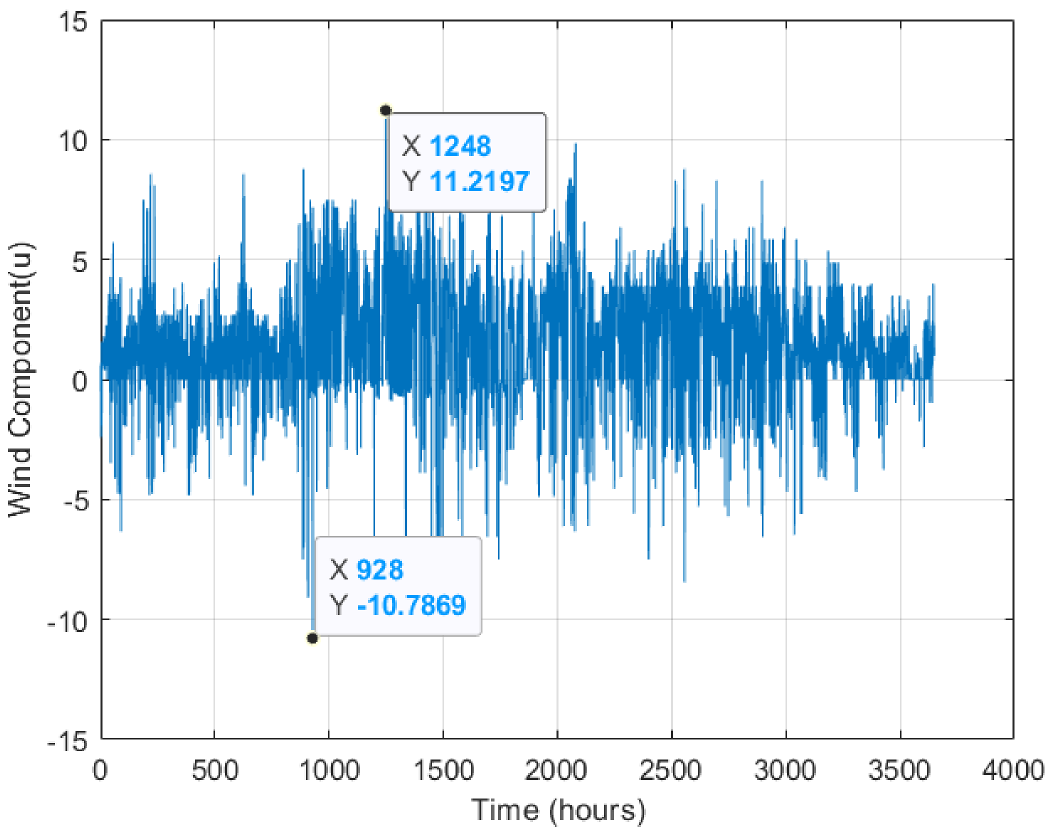

Figure 5: Model results of West-East wind component speed (u)

4.3 Model results of North-South wind speed component (v)

Figure 6 presents the variation of the wind component (v) model at Kadzuhoni area which is characterized by North-South flowing wind. Negative component v means the wind blew from South to North, which characterized the southerly winds, and which is parallel to the y-axis (i.e. latitude). Positive component v means the wind blew from North to South, which characterized the northerly winds. From figure5 it is evident that the southerly winds dominate with a maximum wind speed of 13.47 m/s, while the maximum wind speed of the northerly winds was 11.36 m/s. Therefore, the southerly winds were dominated at the proposed site. These results answered fully the specific objective three. From figure2 above, the study map shows that part of the Indian Ocean lies on the Southern side, which indicates that the southerly winds will carry warm dry air from the Indian Ocean. Combining both model results of u and v wind components the appropriate orientation of the seawater greenhouse can be determined. The results showed that the southerly winds dominated at the study area, hence the seawater greenhouse should face to the Southern direction for optimum hot dry wind collection. These results answer specific objective four.

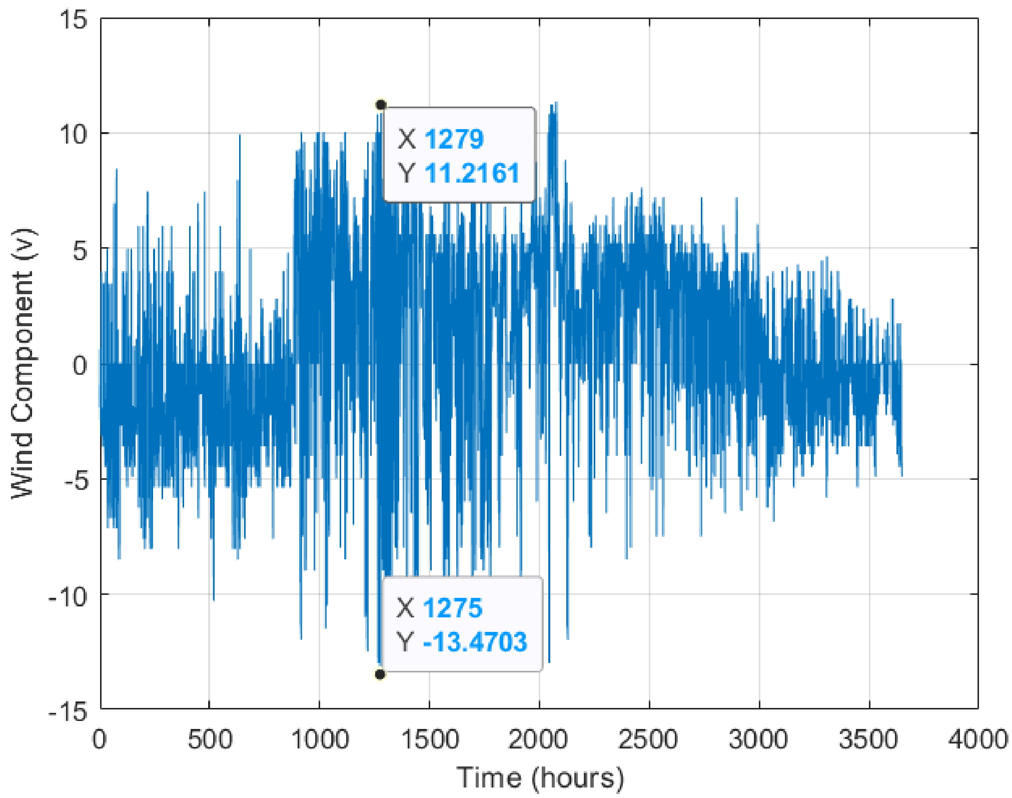

Figure 6: Model result of North-South wind speed component (v)

Figure 7 is a wind rose that indicates the wind speed and direction. The wind rose represents the wind speed and direction of Kadzuhoni area during the period of January 2021-December 2021. From the figure, the resultant wind direction blew from SSE direction at 152 degrees with a frequency of 49%. Calm wind speed had a frequency of 11.79%, the wind speed between 2.10-3.60 m/s is denoted with yellow color, while the wind speed between 3.60-5.7 m/s is denoted with red color. The wind speed between 5.7-8.8 m/s is denoted with blue color, while that of 8.8-11.1 m/s is denoted with green color, and the maximum wind speed is denoted with blue light color.

From the figure, it is evident that the maximum wind speeds as indicated by the blue light colors blew from South, which is the southerly winds. The dominant wind speed as portrayed by the analysis is the southerly winds. These results marry with the model results from Figure5 and Figure6. The direction portrayed by the analysis will be used to set up the prototype of the seawater greenhouse at Kadzuhoni.

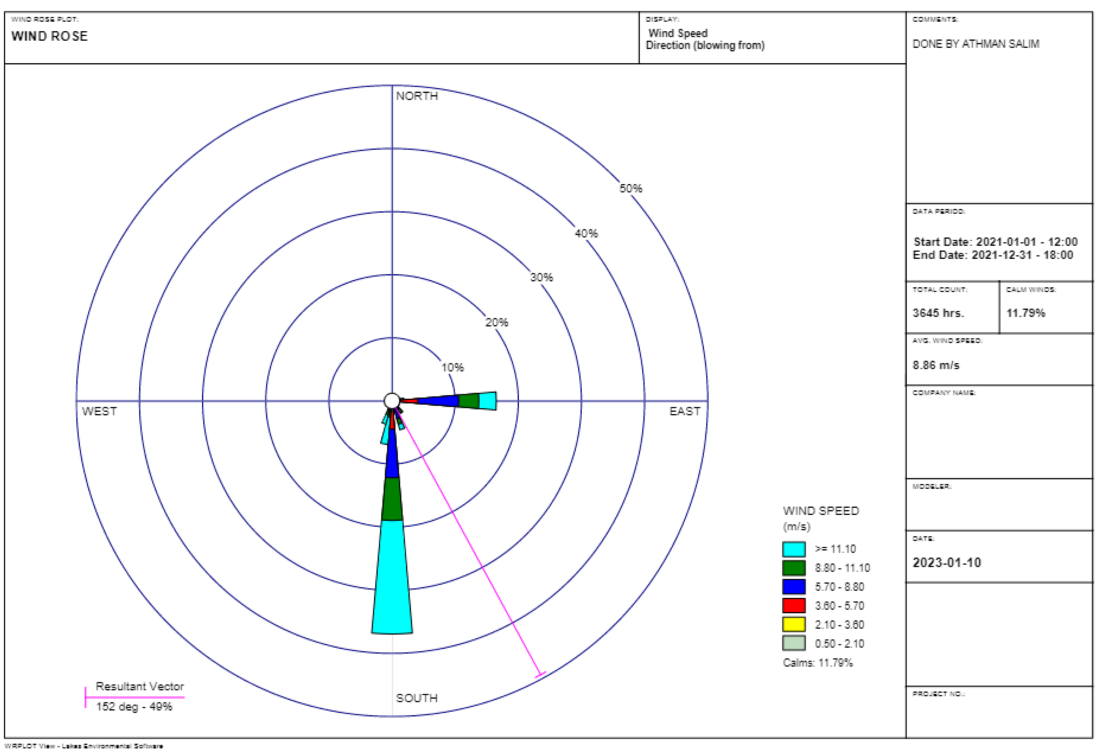

Figure 7: Wind rose of wind speed and direction

Figure 8 presents the general wind class frequency distribution of the proposed site. In general, the calm wind has a frequency distribution of 11.8%, the speed 2.1-3.6m/s has a frequency distribution of 4.9%, the speed 3.6-5.7m/s has a frequency distribution of 12.3%, the speed 5.7-8.8m/s has a frequency distribution of 25.3%, the speed 8.8-11.1m/s has a frequency distribution of 14.8%, while the speed above 11.1m/s has a frequency distribution of 30.8%.

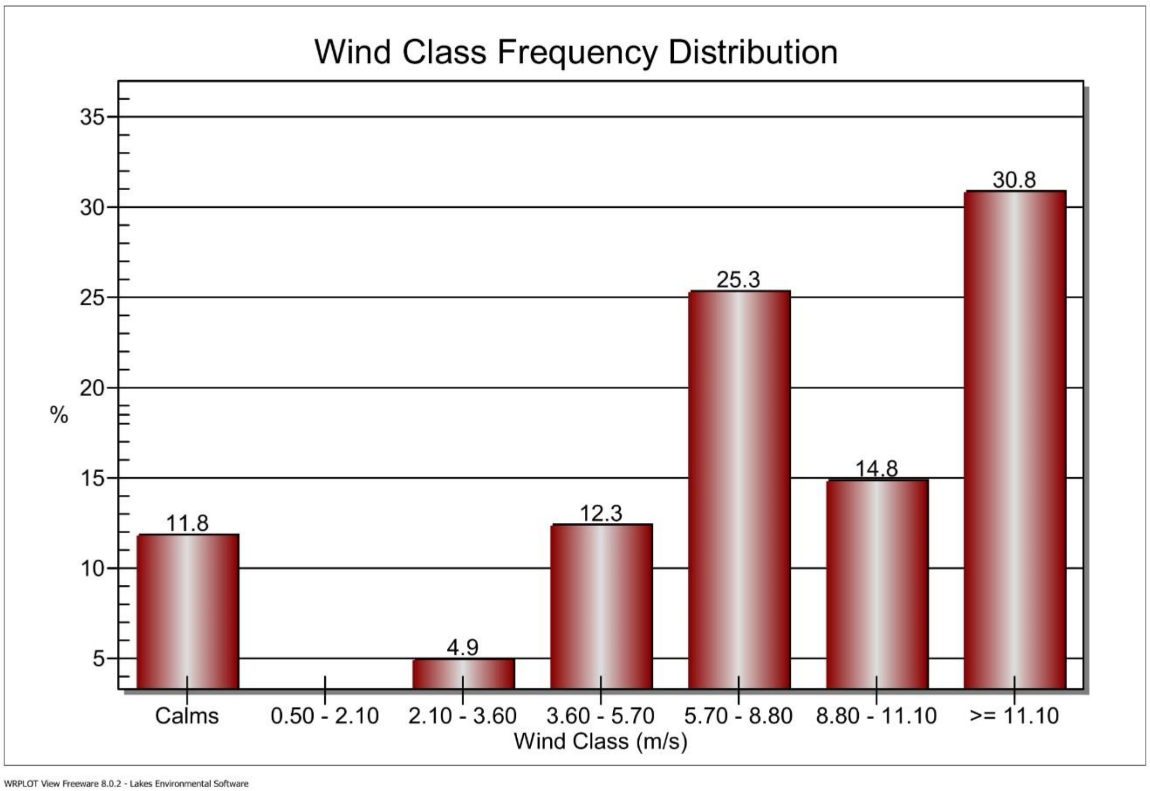

Figure 8: Wind speed distribution from different frequencies

Figure 9 shows validation of the harmonic analysis model performed for the study. The harmonic analysis results were used to validate the model, by using the observed (a) and predicted (b) wind speed values.

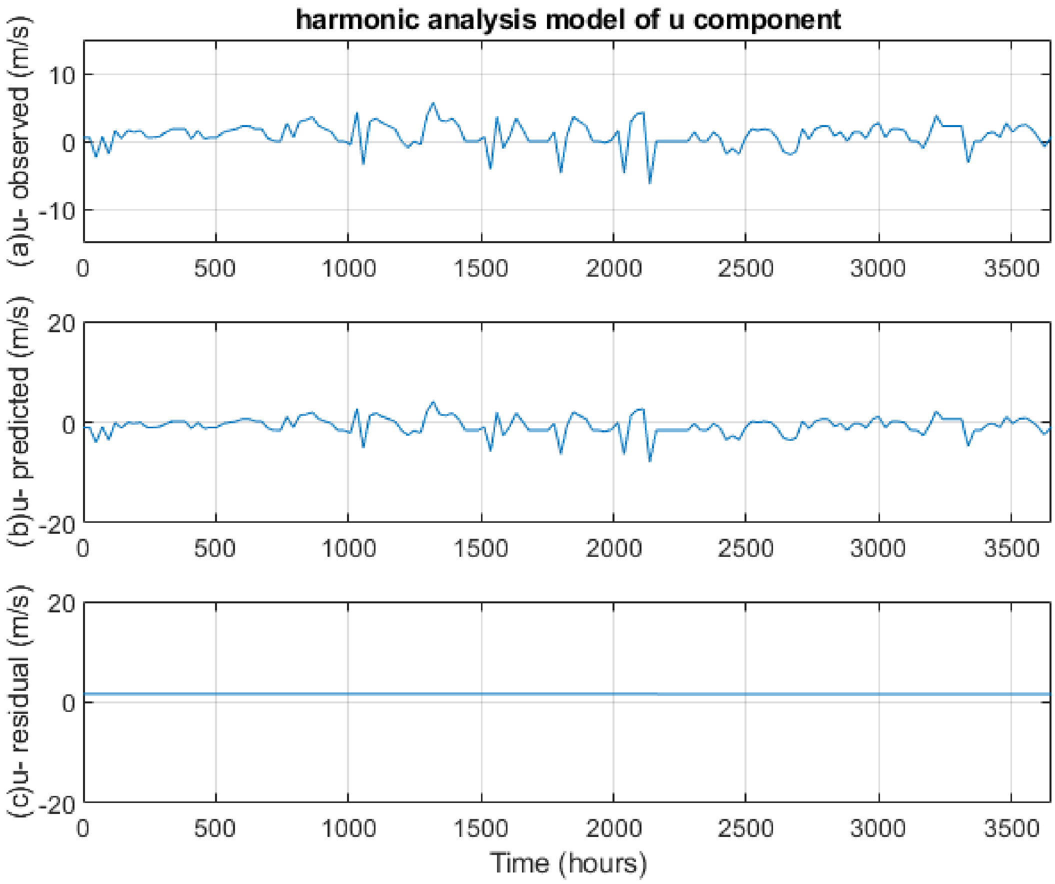

Figure 9: Validation of the harmonic analysis model performed on the wind component (u)

Figure 10 shows validation of the harmonic analysis model performed on the wind component (v). The harmonic analysis results of the model for observed and predicted were also used to validate the model, by using the observed (a), predicted (b), and residual (c) wind speed. From the validation results in Table1, there was no significant difference between the observed and the predicted values and therefore this characterized the model used as a good model.

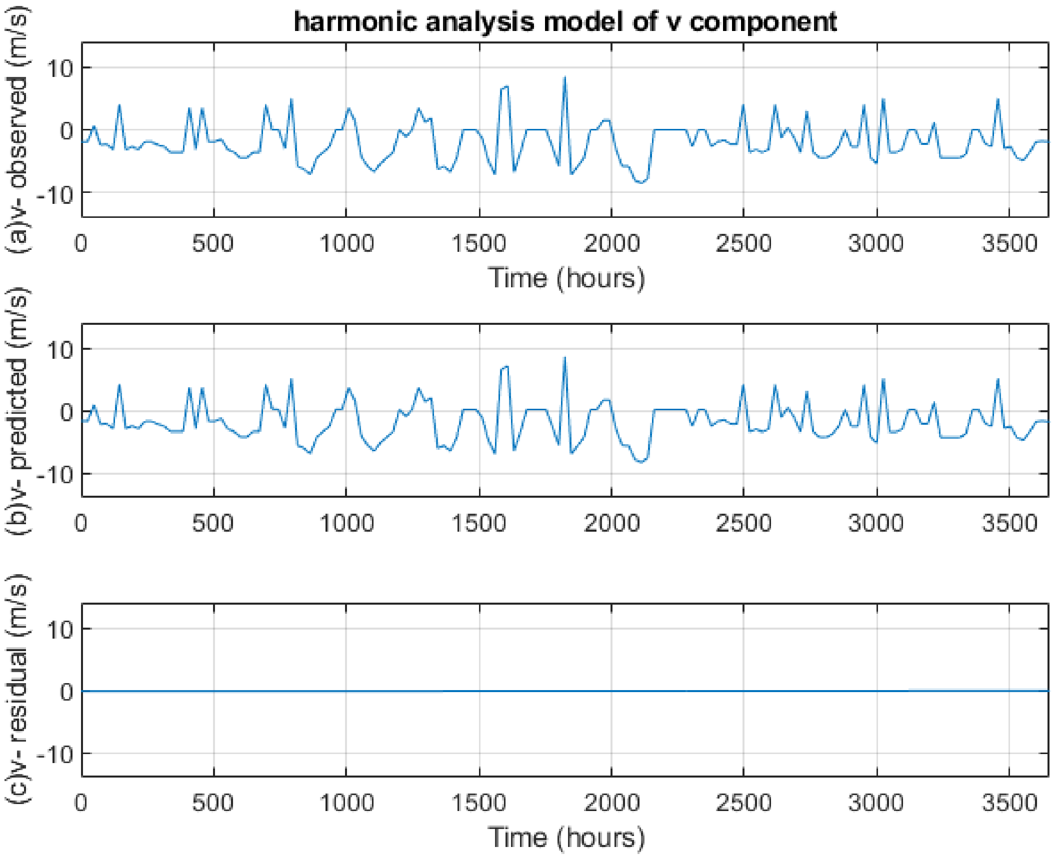

Figure10: Validation of the harmonic analysis model performed on the wind component (v)

Table1, shows the results of the model validation of the harmonic analysis model. It is clear that there was no significant difference between the observed and the predicted values as shown in Table 1.

Table 1. Validation of the harmonic wind speed model

Observed wind speed	2.68	3.13	1.92	1.92	2.40	2.68	3.58	3.58	3.58	-3.48	3.13
Predicted wind speed	2.50	2.94	1.73	1.73	2.21	2.50	3.39	3.39	3.40	-3.66	2.95

Figure11 below shows the periodicity of both u and v wind components of the proposed area. Here, u denoted the easterly wind frequency and v denoted the southerly wind frequency. It is clear that the energy decreases with an increase in the period. Also, it shows that the frequency decreases with an increase in period as indicated by the harmonics from the figure.

The spectral analysis results of u and v indicated the prevailing wind speed frequencies. From the figure it is evident that the southerly winds v velocity frequencies were the ones prevailing in the proposed area. It is evident that the spectral analysis results of v velocity was higher than the u velocity, this is due to the highness and dominance of southerly winds as seen also from Figure6. These results underpin the decision of making the seawater greenhouse facing to the prevailing wind frequency of the southerly winds.

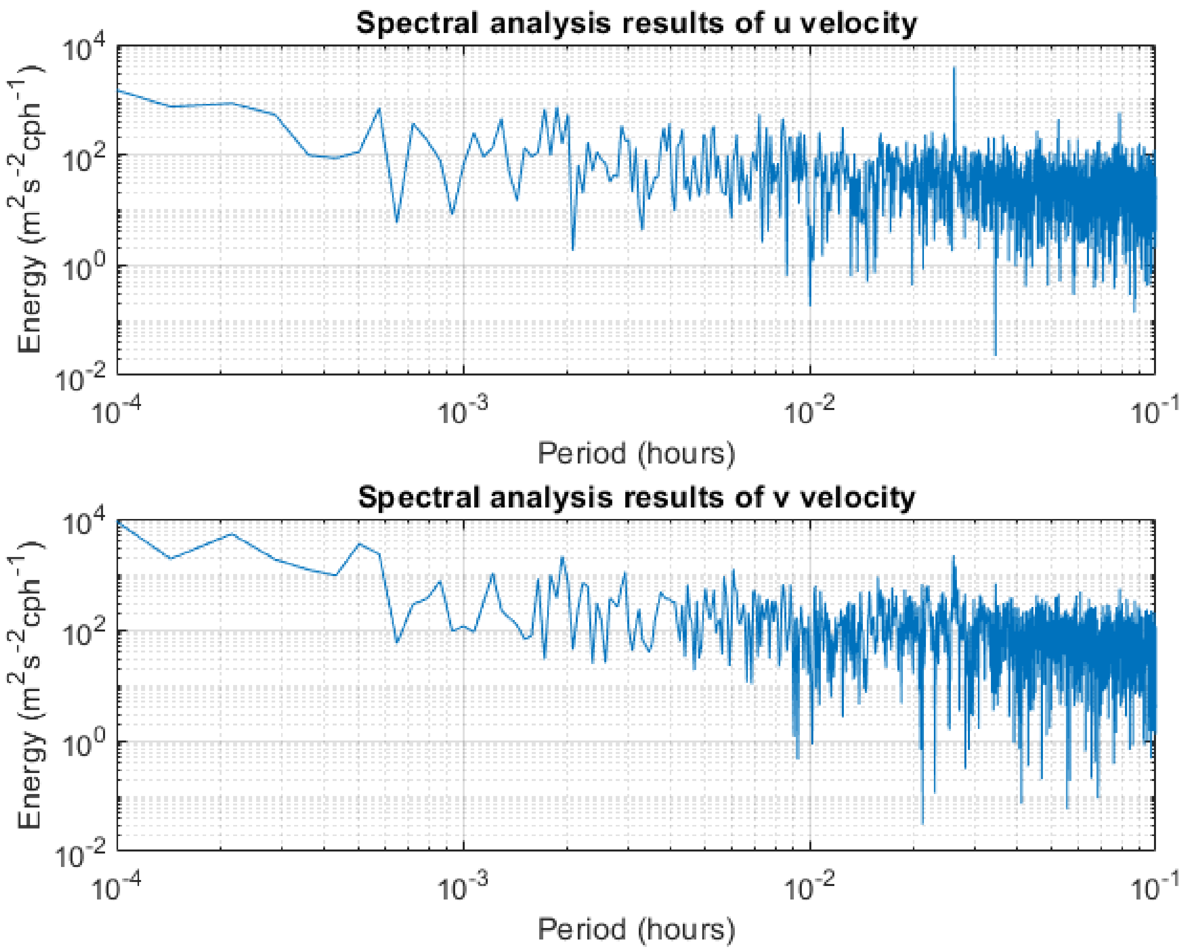

Figure 11: Spectral analysis of u and v wind speed components

Figure 12 shows cumulative distribution functions of t-Location scale and epsilonskewnormal used to show the probability of wind speed denoted with two line, red for t-Location, and blue for epsilonskewnormal. The two lines of fit meet at three different points showing three different speeds at three different cumulative probabilities.

The first point it showed that the probability of getting a speed of 2 m/s was 0.18, and the second point showed that the probability of getting a speed of 6.25 m/s was 0.75, the third point showed that the probability of getting a speed higher than 12.5 m/s was 0.99. These results, therefore, indicate that the study site has high probability of getting high wind speeds, and hence makes the site suitable for the seawater greenhouse set up.

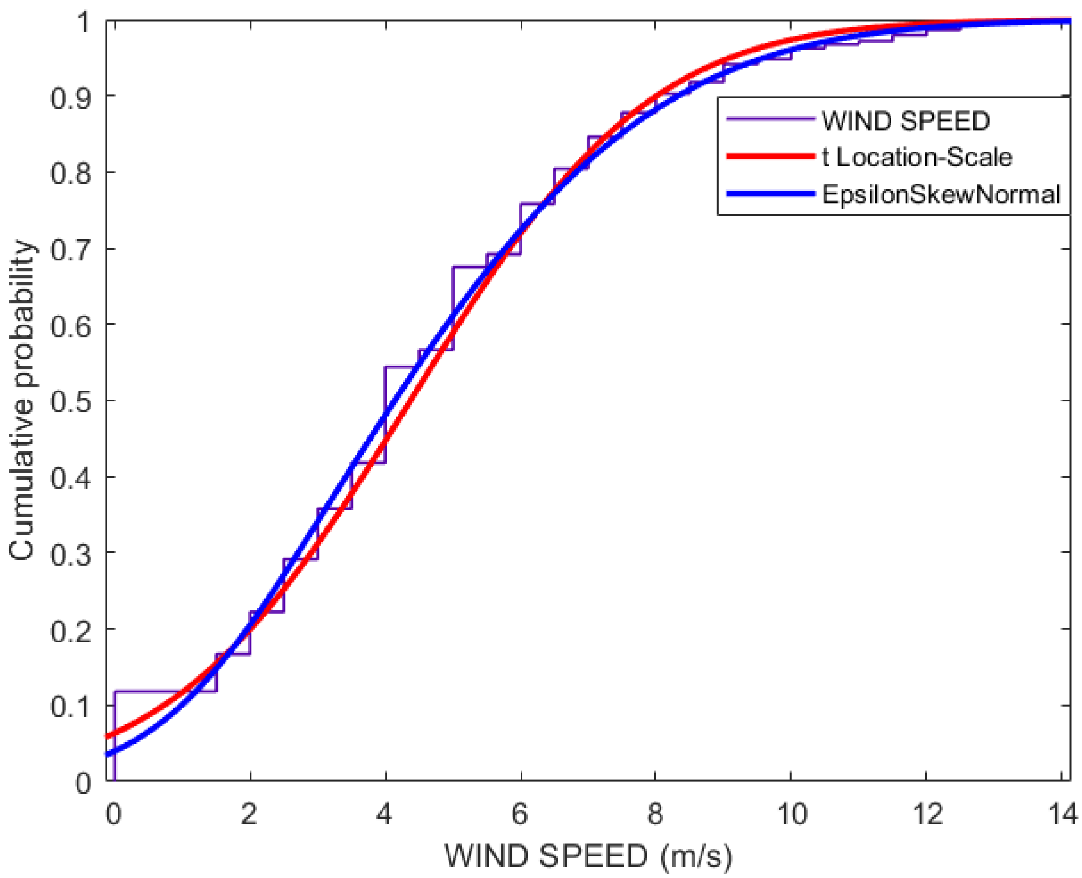

Figure 12: Wind speed cumulative distribution functions of t-Location and epsilon

Figure 13 represents a map of the study area and the results of the wind rose overlaid together. From figure 13, the direction that the wind rose arrows point is the direction which the wind is blowing from the weather station, as also indicated by Figure 7. It can be noted that there are two directions that the wind blew from the weather station, one direction is from the East of the weather station and the other is from the South of the weather station. The dominant wind speed blew from South of the weather station to the Northern side, this means that the seawater greenhouse will receive hot dry wind speed from the South.

Therefore, the seawater greenhouse first evaporative pad will have to face the Southern direction to achieve the maximum wind speed as well as the cooling effects. The position that the seawater greenhouse prototype is to be set, seems to be a good position.

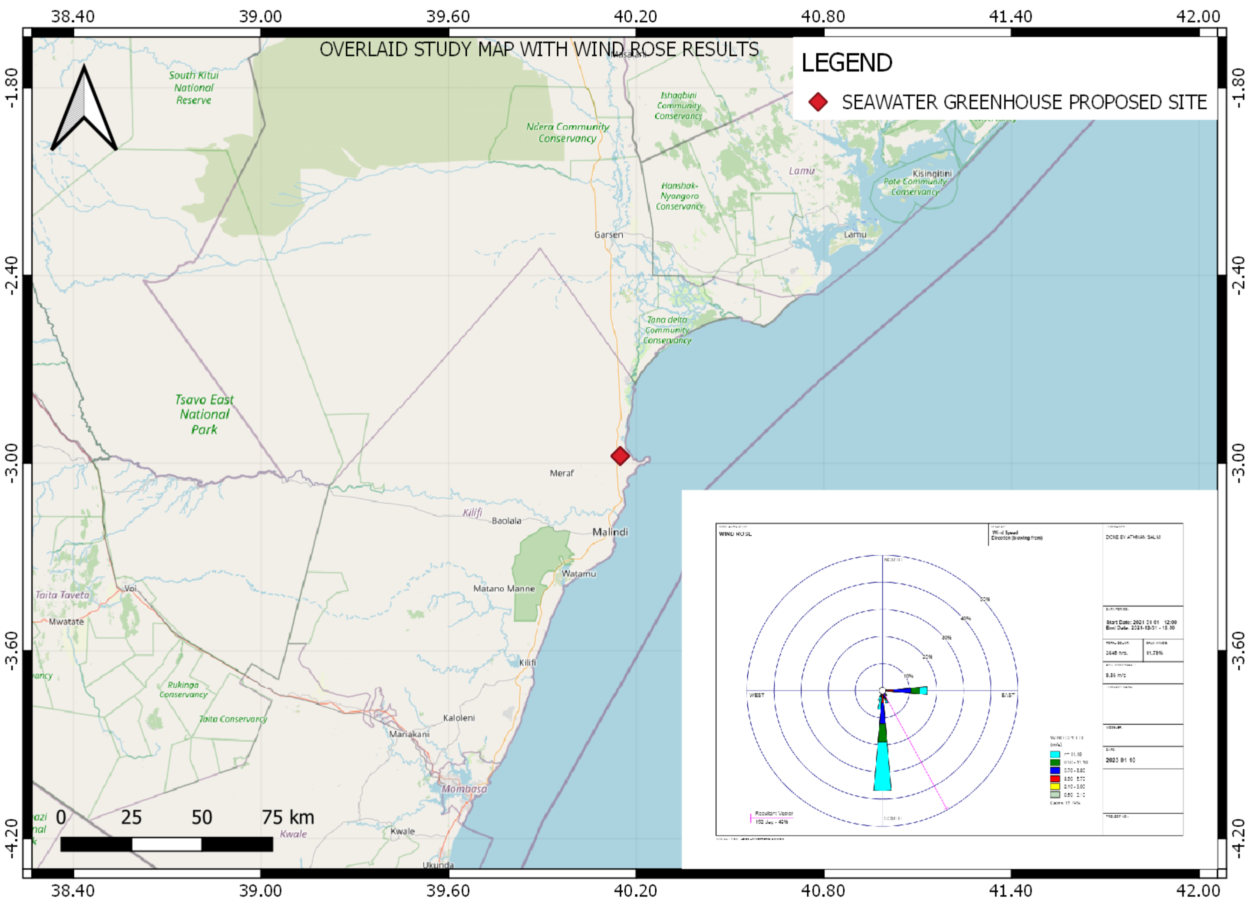

Figure 12: Wind rose results merged with study area map

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1.2. Conclusions

The general maximum wind speed of the proposed site was 14m/s as observed from the results of the time series analysis, while the maximum wind speed for the southerly winds was 13.47 m/s, and that of the easterly winds was 12.22 m/s.

The dominant wind speed at the proposed site was found to be the southerly winds, as it was also confirmed by the wind frequencies from the spectral analysis. According to the proposed site, the East side is the side where the Indian Ocean is, as it is located on the study site map. Some part of the Indian Ocean is at the Southern part of the proposed site, this means that the high southerly speeds wind will be able to carry warm water vapor from the sea to the evaporative pad. The appropriate orientation of the seawater greenhouse's first evaporative pad is the Southern direction for optimal wind speed as well as for cooling purposes to reduce the cost of fan.

From the harmonic analysis model results, as indicated by table1, it is evident that there is no significant deviation from the observed wind speed and the predicted one, and this is a characteristic of a good model

The seawater greenhouse setup should be facing in the Southern direction since it is the direction with the dominant wind speed for it to perform well without the use of fans.

5.1.3. Recommendations.

More studies to be done in the inside seawater greenhouse to determine the extent of the wind flow from the first evaporative pad to the second one after the setup is complete.

There is need to monitor and measure the inside cooling effects of the seawater greenhouse after its completion to understand how well the seawater greenhouse is performing.

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