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The viability of solar power supply: a feasibility study of Monkey Bay maritime base port in Malawi

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THE VIABILITY OF SOLAR POWER SUPPLY. A FEASIBILITY STUDY AT MONKEY BAY MARITIME BASE PORT IN MALAWI

By

JOSEPHINE ELLAH KAMBALE

Malawi

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Declaration

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

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

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ABSTRACT

Title of Dissertation : The Viability of solar power supply. A feasibility study at Monkey Bay Maritime Base port in Malawi

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Lately, global maritime shipping has become a key source of both air pollutants and GHG emissions. These gases are emitted both when ships are in transit and at berth, of particular concern are emissions emitted by berthed ships due to their negative impacts on the environment and local communities.

Monkey Bay Maritime Base port in Malawi depends on electricity supply from national grid for cold ironing or onshore power supply to its berthed ships. Port operations is greatly affected by erratic supply of this electricity due to challenges in generation, transmission and distribution. These challenges generally leads to low throughput and a reduction in competitiveness and profitability in commercial ports. In case of load-shedding, like many African ports, berthed vessels at Monkey Bay Maritime Base port run on their auxiliary engines to produce needed electricity for hoteling services which has significant contribution to air pollutants and GHG emissions which are harmful to humans and the environment as well as increases operating costs due to increase in energy consumption.

This dissertation aims at encouraging decision makers at Monkey Bay Maritime Base port to adopt the use of solar energy for cold ironing as an innovative energy solution that will lower costs, lower energy consumption and negative externalities exerted on the environment and port communities. Onshore power supply is an effective measure of controlling emissions as a berthed ship switches off their diesel-powered auxiliary engines and plug in to shoreside electricity which is emission-free, sustainable and an economical solution especially when sourced from renewables energy sources.

In this thesis, total energy consumption at Monkey Bay Maritime Base port was assessed through a Levelised Cost of Electricity calculator model, then the price sensitivity analysis was calculated and analysed in Monte Carlo Simulation using Crystal ball software. The results shows that the installation of Solar Photovoltaic technology for port usage at Monkey Bay Maritime Base port is a viable option that will mitigate not only environmental but also social and economical issues that emerges due to the use of fossil fuels in port areas.

The research outcome proves that investment of solar energy project for Monkey Bay Maritime Base port in Malawi is a viable option as the area receives abundant sunlight throughout the year. As shown in the paper Monkey Bay has the potential of generating an estimated power output of 55,754.44kWh/year which can be harnessed using 359 solar panels of $330W_p$ each installed on $717m^2$ of land and in the process can offset approximately 90% of the ports electricity bills. With this project in place a significant amount of air pollutants and GHG emissions will be eliminated from the shipping industry.

The calculated results also has shown that in 25years, the power purchase agreement is 0.13742$/kWh while the Levelised Cost of Electricity is 0.00965$/kWh. Since the price of power purchase agreement is higher than that of Levelised cost of electricity, it implies that the project is profitable, Port Authority, the government or independent power producers should go on to invest in this project as it will break even.

KEY WORDS: Photovoltaic, Solar energy, Cold Ironing, Onshore Power Supply, Ship emissions, Levelised Cost of Electricity.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
CAPEX	Capital Expenditures
CO	Carbon Monoxide
CO_2	Carbon dioxide
CORNREMA	Cooperation Network network for Renewable Energy in Malawi
DC	Direct Current
DCF	Discounted Cash Flow
EAPP	East African Power Pool
EGENCO	Electricity Generation Company Limited
ESCOM	Electricity Supply Corporation of Malawi Limited
ESI	Electricity Supply Industry
ESPO	European Sea Ports Organisation
ESI	Environmental Ship Index
EU	European Union
GHG	Greenhouse Gases
GHI	Global Horizontal Irradiation
GWh	Gigawatt-hour
Gigaton	One billion metric tons
GoM	Government of Malawi
HFO	Heavy Fuel Oils
IMO	International Maritime Organization
IPPs	Independent Power Producers
IRENA	International Renewable Energy Agency
kW	kilo-Watt
kWh	kilo Watt-hour
LCOE	Levelised Cost of Electricity
LCOE	Levelised Cost of Energy
LNG	Liquefied Natural Gas
LBCT	Long Beach Container Terminal

MAREP	Malawi Rural Electrification Project
MERA	Malawi Energy Regulatory Authority
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MEM	Maritime Energy Management
CH4	Methane
MMF	Malawi Maritime Forces
MW	Megawatt
MWh	Megawatt-hour
MoNREM	Ministry of Natural Resources, Energy and Mining
MMB	Monkey-Bay Maritime Base
MCS	Monte Carlo Simulation
MIGA	Multilateral Investment Guarantee Agency
NPV	Net Present Value
NO2	Nitrogen dioxide
NO_X	Nitrogen Oxides
OECD	Organisation of Economic Co-operation and Development
OPS	Onshore Power Supply
OPEX	Operational Expenses
O&M	Operation and Maintenance costs
O_3	Ozone
PM	Particulate Matter
PPA	Power Purchase Agreement
PSRS	Power Sector Reform Strategy
PHC	Population and Housing Census
PV	Photovoltaic
RES	Renewable Energy Sources
RETs	Renewable Energy Technologies
SDGs	Sustainable Development Goals
SE4All	Sustainable Energy for All

SAPP	Southern African Power Pool
SO_2	Sulphur dioxides
SO_X	Sulphur Oxides
SMO	System Market Operator
SWOT	Strength Weakness Opportunities and Threats
TEUs	Twenty-foot Equivalent Unit (Container)
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UN	United Nations
USA	United States of America

CHAPTER 1

1.0 INTRODUCTION

1.1 BACKGROUND

Malawi is a landlocked country located in Southeastern Africa bordered by Tanzania, Mozambique and Zambia with a surface area of 118,484 km². It has a population of 17,563,749 people with an annual growth rate of 2.9% as stipulated in Population and Housing Census [PHC] conducted in 2018 (PHC, 2019). Currently, the country has more than 19 million people (Sharma & Benktesh, 2020) estimated to reach 23million by 2025. Malawi's major lakes are: Lake Chiuta, Lake Chilwa, Lake Malombe and Lake Malawi where Malawi Maritime Forces carries out its major operations.

Lake Malawi is the ninth largest and third deepest freshwater lake in the world; it forms part of the eastern African Great Rift Valley. It is 580Km long, 75Km wide at its widest point, 708m deep at its deepest point and 474m above sea level with a total surface area of 29,600Km². The Lake covers the eastern part of the country lengthwise where it borders with Tanzania to the Northern part and Mozambique to the East and Southeastern parts of the Lake where it is also called Lake Nyasa and Lago Niassa respectively. Ruhuhu River is the major inflow while Shire River is its only outlet that drains into Zambezi River in Mozambique that then carries the water all the way into Indian Ocean. Monkey-Bay Maritime Base port is situated at southern end of Lake Malawi in the Southern region of the country. Monkey-Bay, Chipoka, Nkhotakota, Nkhata-Bay, Likoma Island, Chilumba and Karonga are major ports along Lake Malawi that facilitate the movement of both passengers and Cargo.

The energy sector in Malawi greatly relies on hydro-generated electricity, coal, imported fuel oil and biomass to meet its energy demand. 97% of the country's total energy supply is biomass (Sharma & Benktesh, 2020) particularly in the rural areas where it is used as fuel-wood for cooking, curing tobacco and heating homes. Biomass-based energy sources include firewood, charcoal, agricultural and forestry residues (hog fuel) and industrial wastes; its sources are being depleted due to over exploitation.

The country has enormous reserves of coal of over a gigaton of which 22 million are bituminous type which have low sulphur and high ash content (Sharma & Benktesh, 2020; Taulo et al., 2015); Kaziwiziwi, Livingstonia, Mwabvi and Lengwe (Umali et al, 2016) are some of the country's coal mines. Coal is mostly used as a supplementary energy source in industrial production since electricity is unreliable for example in sugar production, textile, beer brewing, cement production and tobacco processing. Additionally, a 300MW coal-fired power plant at Kam'mwamba is under-way.

The national grid electricity is generated by Energy Generation Company limited (EGENCO) and transmitted/distributed by Electricity Supply Corporation of Malawi (ESCOM) parastatal organisations. Recently, the Independent Power Producers (IPPs) especially from renewable sources have been allowed to produce electricity and sale to ESCOM.

Currently, the available electricity generation capacity is 441.95 Megawatts (MW) generated from hydro-power plus 53.22MW generated from standby diesel-powered generators using imported fuel oil since the country has no known oil deposit reserves of its own. The country imports 97% of refined petroleum products, 3% is produced from sugarcane ethanol fuel (Taulo et al., 2015). The current electricity requirement for consumption in Malawi is 800MW, however, only 12% of the inhabitants have access to electricity supplied by ESCOM of which 5.3% represents rural electrification (Eales et al., 2020).

However, the government of Malawi initiated the Malawi Rural Electrification Program (MAREP), the project was meant to increase access and provide affordable electricity especially to the rural areas of the country in order to reduce the use of biomass and fossil fuels by 2025 (World Bank, 2019). At present, more than ~1,500MW of electricity is required to meet the growing energy consumption demand. Consequently, MAREP initiative resulted in straining the existing power supply system to a great extent resulting in frequent load shedding that disrupts manufacturing, interrupts social and economic services as well as deters both local and foreign investments.

This calls for an urgent need to develop and increase access to adequate, reliable, affordable and environmentally friendly alternative power sources to supplement the national grid and reduce the use of biomass, which pollutes the environment and contributes to climate change. Global warming caused by huge amounts of GHGs are currently considered a global environmental issue in return for economic growth. In line with the 2015 Paris agreement on climate change, the shipping industry and the energy sector should play their role to keep the limit of global warming below 2°C as compared to the pre-industrial levels (IPCC, 2018). The energy sector in Malawi in 2005 contributed 68% of global GHGs emissions (Gamula et al., 2013). Shortage and lack of access to affordable and clean energy remains to be a major constraint to economic growth in the country hence the need to accelerate feasibility studies of potential renewable energy sources to reduce reliance on fossil fuel based energy sources.

Harmful air pollution from marine transport is another hot issue in the shipping industry that should be addressed with urgency. Air pollutants causes human health problems especially port workers and residents near the port viz: Sulphur-Oxide (SO_X), Particulate Matter (PM), Carbon-monoxide (CO) and Nitrogen-Oxide (NO_X) while GHG causes environmental issues namely Carbon-dioxide (CO_2), Methane (CH_4), and Ozone (O_3). These toxic gaseous-emissions can be reduced through harnessing renewable energy sources (RES) from the sun, wind and waves, geothermal and hydro-generated. Thus, this research paper analyses the viability of solar energy resources to be adopted at Monkey-Bay Maritime Base port in Malawi.

1.2 PROBLEM STATEMENT

In spite of the various efforts by the government and various stakeholders to improve access to contemporary clean energy, 89% of the energy in Malawi is currently sourced from conventional biomass mainly wood-fuel, charcoal and fossil fuels (Zalengela et al., 2014). High demand for biomass and unsustainable agricultural practices has led to deforestation and desertification that has gradually resulted in environmental degradation resulting in soil erosion and siltation. In addition, extreme weather events (draughts and floods) and invasive weeds (water hyacinth) has also negatively influenced hydro-power generation, which has affected electricity supply to the national grid. The national grid also suffers from losses due to long distance transmission through the use of degraded infrastructures.

Fossil fuels which were formed millions of years ago have for over 200 years now provided humanity with 80% of the energy required to carry out dairy activities. Carbon which is contained in fossil fuels is released into the atmosphere during extraction, transportation, processing and actual usage. The excessive use of fossil fuels create negative externalities to the environment and human health. Environmental impacts include toxic air and water pollutions, soil and land degradation, ocean acidification, destruction of the ecosystem, global warming and climate change due to burning of fossil fuels which in turn traps heat in the atmosphere. Examples of human health problems are lung and heart diseases, cancer, asthma, birth defects and neurological damage.

If we continue burning fossil fuels at the current rate without using carbon capture and storage technologies, 750 billion tonnes of carbon will be emitted to the atmosphere and all reserves of oil and natural gas will be depleted in 50 years and that of coal in 115 years (Ritchie, 2017). Since fossil fuels are greatest contributor of global warming, the below 2^{o}C global climate target can be achieved if two-thirds (75-80%) of current known fossil reserves are left untouched in the ground. It is high time fossils gets replaced with more sustainable RES which are harmless to the environment or processed further into alternative fuels which are more environmentally friendly like hydrogen, ammonia and Liquefied Natural Gas (LNG).

On the other hand, if fossil fuels are used efficiently, consistently and sufficiently there will be a remarkable reduction in negative externalities (air pollutants and GHG emissions) local communities near port locality; plus the future generation will be able to use the untouched reserves to supplement their energy need.

Monkey Bay Maritime Base (MMB) Port is powered by electricity from national grid which is used for cold ironing to berthed vessels, air conditioning, powering the office buildings, workshops, warehouses and other buildings collocated to the port. This power is subjected to frequent load-shedding which forces the ships at berth to run on auxiliary diesel-powered engines to provide power needed for hoteling services in the process emitting harmful GHG and air pollutants. This can be mitigated by using Onshore Power Supply (OPS) or cold ironing from RES which has the potential to reduce hazardous emissions, improve the ports energy efficiency by reducing energy consumption from the national grid. The use of solar energy can decarbonise maritime sector as well as limit the impacts of climate change and global warming.

Therefore, this thesis intends to find a permanent and sustainable solution to reduce air pollution with regard to energy demand and supply to a berthed ships at MMB port by exploring the feasibility of solar irradiation that Monkey Bay receives throughout the year. In addition, the extra power generated with solar photovoltaic (PV) will be fed into the national grid as supplement to meet the growing energy demand nationally, this is a long term solution to the country’s energy problem.

1.3 RESEARCH OBJECTIVES

This thesis is aimed at exploring the possibility of generating solar power at MMB port in Malawi based on the following objectives:

- To analyse the potentials and viability of solar energy to power MMB port and supply the excess electricity to the national grid hence increasing the access to clean and affordable energy.
- To motivate energy stakeholders especially in the private sector to invest in renewable energy technologies and create several micro-grids that would supplement the national grid to meet the current and future energy consumption demand of the country.

1.4 RESEARCH QUESTIONS

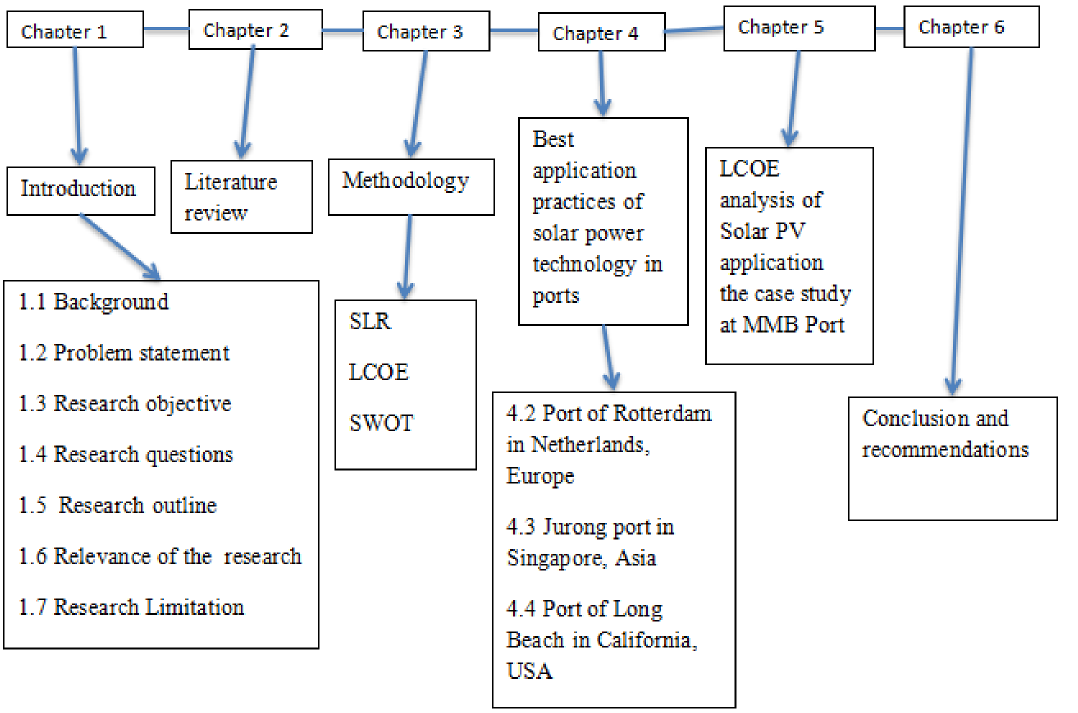
The research questions below will be tackled to attain the specified objectives:

- What is the viability of solar energy at MMB port?
- How much electricity can be produced by solar and used for cold ironing at MMB port?
- What are the potential barriers and drivers for using solar energy at MMB port?

1.5 RESEARCH OUTLINE

This dissertation paper is composed of seven chapters organised in this order: Chapter 1 introduces the topic under study by giving the background information, problem statement, objectives, research questions, outline of the research, relevance and limitations of the research. Chapter 2 contains a systematic review of existing literature on the viability of solar energy. The methodologies used in the study to achieve the research objectives are described in chapter 3 while chapter 4 discusses the best application practices of solar power technology in ports. LCOE analysis and application of solar PV energy at MMB port (case study) is presented in chapter 5. Lastly, chapter 6 discusses findings, conclusions and recommendations for further studies. The summary is as shown in figure 1.

Figure 1: Research approach



Source: (Author, 2021)

1.6 RELEVANCE OF THE RESEARCH

The research is beneficial to the government of Malawi at large as it is in search of viable and alternative energy sources to end the energy crisis that the country is currently facing. Solar is the most ideal source as it is environmentally friendly as compared to coal and diesel-powered generators which are environmentally unfriendly and causes health problems in humans. Once solar PV is in place the generated electricity will contribute to the development of the national economy as many investors are willing to invest in a country with stable and reliable power supply.

1.7 RESEARCH LIMITATIONS

This research paper focuses on performance of all military vessels at MMB port whose energy demands whilst on berth are targeted to be met by cold ironing using solar power. Energy demand by non-military vessels calling MMB port whether during emergency or at will are not addressed in this thesis paper. The research does not address the noise reduction potential due to use of OPS; since OPS is known to reduce noise from berthed ships as both main and auxiliary engines of the vessel are not running.

The research also focuses on electricity supplied to the office buildings that are directly linked with port operations. However, residential buildings near the port will benefit from the excess electricity which will be fed to the national grid. The research does not focus on how long the ship stays at berth considering the nature of the port under study and so, the cost benefit analysis on harmful air emission reduction was not calculated. On the other hand, total port's energy consumption was assessed to lay a foundation of comparison with an ideal renewable energy scenario and come up with the best practice to be adopted by the port. This paper has focused on assessing the viability of solar energy for cold ironing; benefits and drawbacks of using solar energy for ship-port operations at MMB port.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 MARITIME EMISSIONS, CAUSES, ITS IMPACTS AND HOW IT CAN BE MITIGATED

Maritime shipping play a critical role in facilitating 90% in volume (Wang et al., 2021) and over 70% in value (UNCTAD, 2017) of global seaborne trade as it is the most economical and fuel efficient mode of transportation globally. Passenger (cruise and coastal ferry/short sea) shipping comprises 2% of world tonnage. Despite its positive contribution in world prosperity and productivity, shipping also brought negative externalities on humans and the environment. According to the study conducted by International Maritime Organization [IMO] (IMO, 2009; Corbett et al., 2007; Eyring et al., 2005), shipping accounts for global emissions of approximately 15%, 5-8% and 2.2% of NO_X, SO_X and CO_2 respectively. In 2007, approximately 870 million tonnes or 2.7% of total global CO_2 emissions was estimated to have been emitted from international shipping industry (IMO, 2009).

Shipping is a derived demand that emanates from national or international trade of goods and services (Ma, 2021), this means that shipping would not have existed without trade. Therefore, as global trade increases, harmful emissions from Shipping industry are also expected to increase by 50%-250% by 2050 as compared to 2012 levels (Kumar et al., 2019) if necessary actions are not taken into consideration. Similarly, the passengers exposure to negative externalities emitted from passenger ships depends on its movement and how long it stays at berth or anchorage (Dragovic´ et al., 2015). According to past studies, shore-based inhabitants may be affected by emissions emitted several miles at sea depending on climatic conditions and geographical locations, nevertheless, air emissions near the port vicinity has even much greater negative footprints.

Key sources of air emissions from international maritime shipping originates from main engines, boilers and auxiliary engines during navigation and when the ship is at berth. Ships consume huge amounts of low quality fuels (bunker oils) with very high sulphur content such as Marine Gas Oil (MGO), Heavy Fuel Oils (HFO) and Marine Diesel Oil (MDO) as they manoeuvre from one port to another; in the process they emit air pollutants and GHGs emissions.

When the ship navigates from one port to another it uses the main engine to provide power for propulsion, while at berth the main engine is turned off and auxiliary engines are turned-on to provide power demanded onboard and for port related activities like lighting, cooling/heating, cargo handling, system controls and other hoteling services. Ships' emissions creates a series of urban air pollution that causes human health issues like birth defects, cardiovascular and respiratory diseases more especially to residents surrounding the port area, crew members and port workers causing millions of death world-wide, necessary measures must be taken to preserve a clean and health environment. In that regard, IMO has put several systematic technical and operational measures in place to reduce GHG emissions from international maritime shipping by utmost 40% by 2030 aiming for 70% by 2050 (IMO, 2019) and 90% by the end of the century compared to 2008 emission levels.

A study conducted by cooper (2003) as cited by (Hall, 2010) shows that a ferry carrying 2400 passengers during its 10.5hours at berth burnt 3754kilograms (kg) of fuel consuming 15,420kWh of electrical power; in the process it emitted 12.050kg, 16kg, 260kg and 35kg of CO_2, CO, NO_X and SO_2 respectively. Similarly, in another study conducted in 2012 at port of Shenzhen in China they found that berthed container ships emitted 3400, 4200, 400 and 200,000 tonnes of NO_2, SO_2, PM and CO_2 respectively (Wang et al., 2015). However, in 2020 OPS was introduced at the port and a reduction of 88%, 94%, 95% and 37% of SO_2, NO_2, PM and CO_2 respectively was observed as compared with the use of diesel-powered auxiliary engines. (Zis et al., 2014) found that at a typical container terminal in-port emissions for all berthed ships can be reduced by 48-70% for CO_2, 3-60% for SO_2, 40-60%

NO_x, and 57-70% for Black Carbon (BC). Note also that the use of shoreside power supply may eradicate noise, smell and oil pollution in the port locality.

The above-mentioned issues can be addressed by connecting berthed-ships to OPS. In this case, the berthed ship utilises electricity from shoreside to meet the energy demanded onboard instead of using auxiliary engines that run on low quality conventional fuels. To completely eliminate priority pollutants and GHG emissions it is recommendable that shoreside electricity must be generated from RES. Generation through conventional energy sources like nuclear, coal and fossil fuels must be reduced as air emissions are only transferred from maritime to land-based sources. Consequently, using OPS from RES is anticipated to bring a remarkable reduction in these emissions and become a mandatory service for most ports to adopt (Fang & Wang, 2020), for example in Europe all ports are required to have provisions of OPS by the end of 2025 (Zis, 2019). According to World Ports Climate Initiative [WPCI] (WPCI, 2018) as cited by (Gutierrez-Romero et al., 2019) only 30 ports have the provision of OPS installation in place globally as of 2019. It is therefore a responsibility of every state to enforce different strategies to curb air pollution from shipping industry be it landlocked country or coastal states. It is a fight that should be fought with togetherness as pollution can affect inhabitants miles away from the point of pollution. Therefore, adoption of cold ironing will improve air quality in port locale and cities as emissions of pollutants and GHGs are mitigated (Esteve-Pérez & Gutiérrez-Romero, 2015).
OPS is a sure option of eliminating these poisonous emissions from shipping industry without affecting economic growth and ensuring the sustainability of fossil fuels since its sources are being drained considering the current rate of consumption.

2.2 HISTORICAL OVERVIEW OF SOLAR ENERGY

The sun is an extraordinary source of all the energy the earth consumes ranging from fossil fuels i.e. dead plants and animals which died billion years ago as well as renewable energy sources in the form of heat and light which can be converted into electricity. Solar energy is a clean renewable energy source which is harnessed directly from the sun even on a cloudy or rainy day and converted directly into electricity using Photovoltaic cells. According to McLamb (2011) as cited by (Salem & Seddiek, 2016) nothing would exist on earth without the sun since animals eat plants, plants depend on the sun to make food and they are both key ingredients for fossil fuels. Fossil fuels provide much needed energy for day to day activities for survival of humanity on this planet, however its sources are being depleted as it is not extracted sustainably and its usage has brought more environmental harm than benefits in form of air emissions.

2.3 LAYOUT OF SOLAR PHOTOVOLTAIC (PV) SYSTEM

A typical model of grid-connected solar PV system which can be connected at maritime ports is as shown in figure 2 and figure 3. It comprises of four fundamental elements specifically: photovoltaic modules or panels, inverter, battery bank, charge controller and other electric devices. Solar panels are devices made up of PV cells which collect solar energy from the sun converts it directly into electricity. PV surfaces neither have moving parts to wear out, suffer breakdowns or generate noise/vibrations nor do they use fuels that would harm the environment. The only fuel they use is the sun that is clean, harmless and in abundant. Batteries are used to store extra power generated by modules for later use i.e during overcast, at night and on days with low sunshine. Charge controller controls the charging rate of the batteries, it prevents the batteries from being discharged fully or overcharged in the process increasing the battery's useful lifespan. The alternative of batteries is to connect the system on-grid. An inverter converts the generated power from Direct Current (DC) to Alternating (AC) that is compatible to voltage levels and network frequency (Seddiek, 2019), AC is a form that most electrical appliances in homes/ports uses.

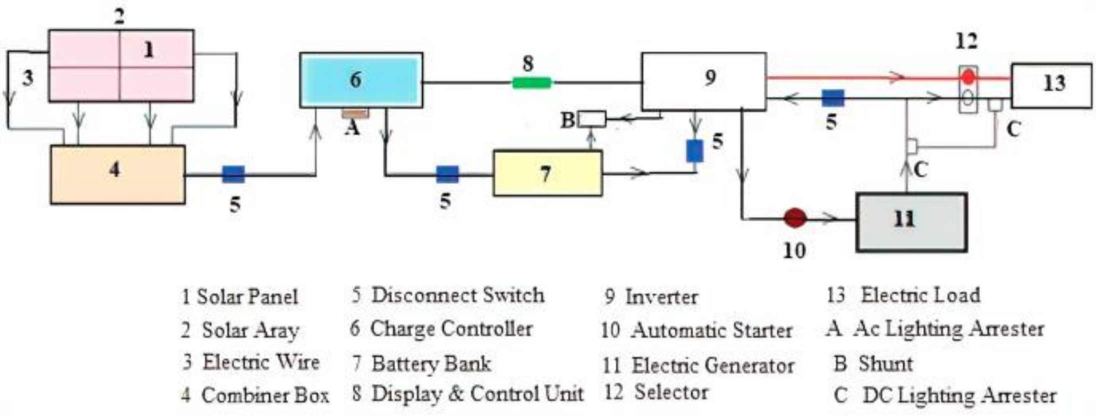


Figure 2: Simple model of a grid-connected PV system (Seddiek, 2019).

On top of that, to connect ship to shore the following equipments are needed: shore-to-ship cables, safety interlocks, circuit breakers, switchgear, receptacles, converters, plugs as well as communication and power equipments. In figure 3, the consumption include connection to berthed ships.

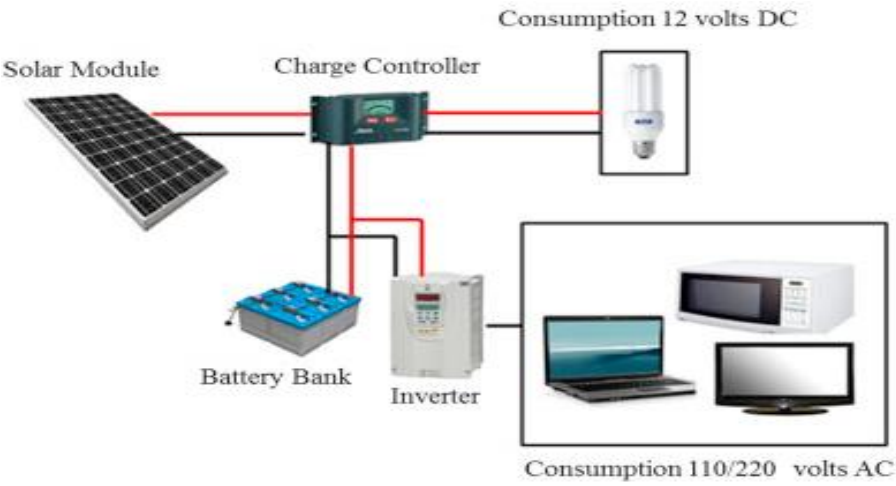


Figure 3: Typical System of photovoltaic solar energy (Sampaioa & González, 2017).

2.4 DRIVERS AND BARRIERS TO INVESTING IN SOLAR ENERGY TECHNOLOGY

There are several drivers/benefits of solar energy viz: It is an efficient power source as the generation plant will be closer to the end-users there will be zero power losses and with the use of batteries extra power can be stored for later use; It enhances energy savings, reduce energy bills, improve energy independence/self sufficiency; It is environmentally friendly, noiseless; the panels require less space, has a lifespan of 20-30years with low maintenance and operational costs and can be installed almost everywhere; It increases employment opportunities and boosts the country's economy as the rate of importing fossil fuels is reduced.

In the past lack of sufficient area for solar PV panels installation and lack of storage capacity for generated power were the biggest limitations to invest in solar energy technology. Currently, panels can be installed almost everywhere ranging from rooftops, in water as floating panels and ground mountings. Additionally, batteries are used to store excess generated power for later use or connecting to the national grid so that electricity supply is not interrupted. It is extremely important to find low-cost ways of storing power since batteries are quiet expensive.

In spite of a higher purchase and installation cost, the use OPS from solar energy posses a technical challenge for port operators and the facility must be compatible with various berthed ship types/sizes. Therefore, ship-port operators must be equipped with technical skills to deal with compatibility issues before investing in the technology. Because of the above-mentioned technical and economical barriers most ports with a wide variety of ship sizes and types with several small berths are reluctant to invest in the OPS technology let alone from solar energy. As a solution to the aforementioned issues, the technology must be installed on selected terminals targeting selected type and size of ships mostly cruise, container terminals and warehouses that store perishable products.

In light of the aforesaid barriers, the government should formulate laws and policies that promote deployment of solar PV in ports in order to preserve the environment without compromising economic growth and development. Policy makers can achieve this by employing three types of instruments namely regulatory approach command and control; Economic incentives or market based policies; and hybrid approach (Wang et al., 2021). Usually, incentives are given to ships which has portrayed very high environmental performances while using shoreside power supply under differentiated port charges as is done in most European Union (EU) ports.

Regulatory approach is a standardised customary design that mandates particular products, processes and technologies that polluters must adopt with the aim of reducing their emissions. On the other hand, economic incentives are attractions that motivates polluters to reduce emissions by receiving a financial award in form of fees, emission taxes and subsidies that encourages them to stop polluting the environment. Hybrid approach is a combination of economic and regulatory incentives where the polluter is allowed to pursue the most financially attractive emission control strategies to them. This is the most captivating strategy likeable by policymakers. For example, as per EU directive 2014/94/EU, a mandatory requirement was issued for EU ports to adopt the OPS installation by the end of 2025 unless there is no demand for such facility or if the cost is too expensive as compared to the environmental benefits that may come forth ("European directive", 2014). To comply to such a stringent directive, Sweden, Norway and Germany adopted and implemented the tax exemptions, tax cuts and financial subsidy policies to assist their ports to develop and expand their infrastructures for OPS as stipulated in International Transport Forum [ITF] (ITF, 2019). In 2018, the port of Bergen secured US$5.9 million from state-owned grant scheme Enova, with the funding three OPS points were built bringing the total to fifteen hence the largest OPS facility in Europe (Gibson, 2018).

The introduction of emission taxes and subsidies has helped the regulatory authority to minimise the environmental impacts caused by berthed ships. For these policies to work effectively there must be a coherent synergy between port entity, regulatory agency (Wang et al., 2021) and shipowners to adopt and implement OPS investment especially from renewable energy resources. The government should play its part to provide incentives that would encourage port authority to invest in solar technology. Port Authority must also create favourable conditions for the ship owners to be willing to make necessary changes like retrofitting and let the technology achieve its intended purpose. Port governance should also exercise its authority to encourage these three entities to play their roles as the technology benefits the environment, society and the economy (Zhang et al., 2018). The initiative by these four entities will collectively lead to the achievement of mitigating toxic emissions from berthed ships and national/international shipping industry as a whole. For instance, the Environmental Ship Index [ESI] a tool used by world's ports to identify seagoing vessels that meets or/and exceeds IMO air emission standards and rewards or incentivise the shipowners, figure 4 shows ESI Participants (ESI, 2021). This is a fruitful collective effort towards mitigating global emissions from shipping industry considering the involvement of more than four continents.

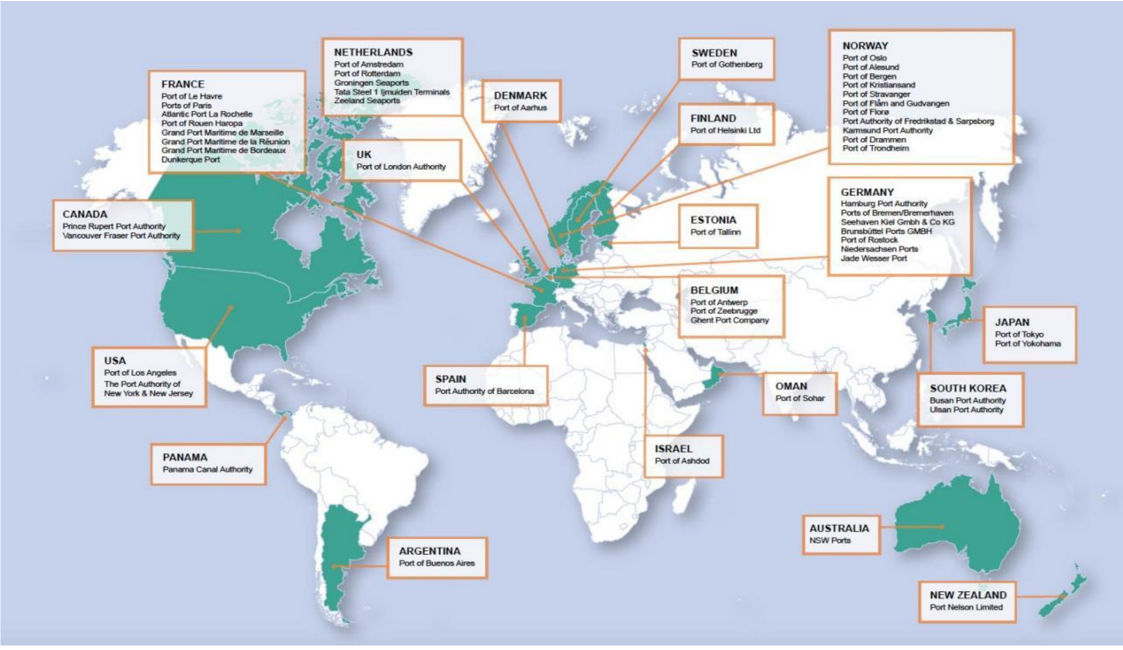


Figure 4: Participating ports in ESI (ESI, 2021).

2.5 THE ENERGY SECTOR IN MALAWI

The country's energy sector was dominated by the state-owned, monopolised and vertically integrated utility company called Electricity Supply Corporation of Malawi (ESCOM) which operated all generation plants, transmission and distribution infrastructures since its establishment under the companies act of of Parliament in 1957 revised in 1963,1984, and 1998 (Kachaje et al., 2017). The structure is as shown in figure 5.

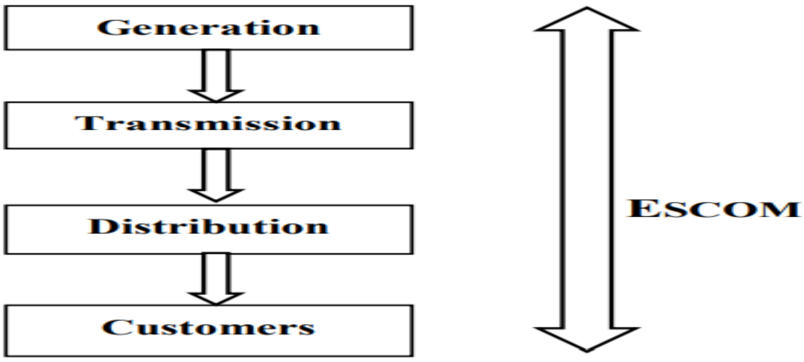


Figure 5: The structure of ESCOM (Kachaje et al., 2017).

Within the past years, increase in population growth coupled with enormous environmental degradation negatively and severely impacted the operation efficiency of electricity generation plants in the country. The power sector experienced several challenges due to monopolistic electricity structure, poor management and under-developed services, lack of competition from private sector, lack of government interest to invest in off-grid electricity generation. The above-mentioned challenges reduced access to affordable, reliable and sufficient electricity (Promethium Carbon, 2016). Another challenge was that the national grid was not interconnected to neighbouring countries hence unable to trade power. A green light was seen after the approval of the Power Sector Reform Strategy (PSRS) in 2003 where private sectors were allowed to participate in power generation but were not active until 2016.

Nevertheless, in 2016 the country adopted the new power market structure where ESCOM was unbundled into: EGENCO and ESCOM, their functions will be emphasised later in this research paper. This allowed more players to enter into the power market with prospects of improving access to electricity and meet the country's production demand. In that regard, the Electricity Supply Industry (ESI) has seen the birth of more actors in the power market like IPPs, several public-private agreements and international agreements.

2.5.1 THE MALAWI POWER MARKET STRUCTURE

The structure of power sector in Malawi is guided by national energy policies and energy laws. The hierarchy shown in figure 6 depicts all the respective bodies involved in the country's power generation that ranges from ministerial level, power generators/suppliers (EGENCO, IPPs and SAPP), transmitter/distributor (ESCOM) to end-users (customers).

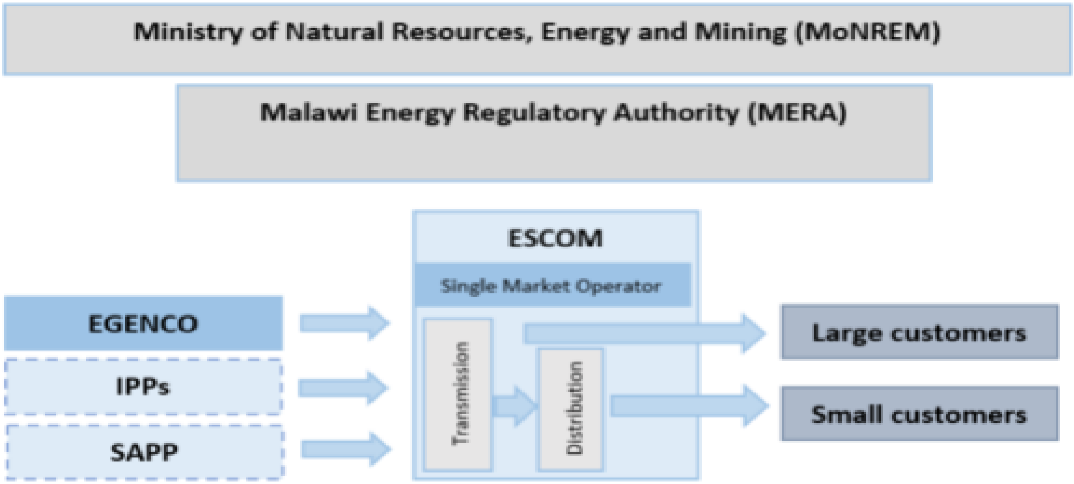


Figure 6: Structure of the Malawi power sector (World Bank, 2019).

The Ministry of Natural Resources, Energy and Mining (MoNREM) is the overall overseer of the electricity sector. The Malawi Energy Regulatory Authority (MERA) is an independent corporate body established in 2007 by Section 3 of the Energy Regulation Act No. 20 of 2004 with the mandate to regulate the energy sector in a fair, transparent, efficient and cost-reflective manner for the benefit of the consumers and operators (MERA, 2021). In other words, it is the overall energy regulator in the power sector of the country. MERA operates under four principal pieces of legislations which are collectively referred to as the Energy Laws of 2004 viz: the Energy Regulation Act, the Electricity Act, the Rural Electrification Act and the Liquid Fuels and Gas (Production and Supply) Act. MERA scrutinises Economic or financial, technical and legal issues laid out in the PPAs thereafter approves them before coming into effect or before ESCOM signs them.

EGENCO and IPPs are two main players in the electricity generation sub-sectors in Malawi. EGENCO is a government owned power generating company, the main player in the country's hydro-powered electricity generation while IPPs are privately-owned electric power producers especially of renewable energy like solar and wind energy. They both sale their generated power to ESCOM the one and only single buyer (off-taker) that further transmit and distributes it to end-users. Southern

African Power Pool (SAPP) is another potential supplier of electricity to ESCOM hopefully in the near future.
IPPs were accommodated by MERA following the development of three regulatory tools namely: tariff methodology, grid code and market rules. The IPPs ventures into a 20 to 30years Power Purchase Agreements (PPAs) with ESCOM depending on the type of electricity generating technology i.e. solar, wind, coal, hydro, nuclear and so on. No PPA is signed before approval by MERA. Since the country follows the single buyer electricity model, IPPS cannot sale their power directly to end-users but through ESCOM. The participation of private sector in power generation has facilitated the exploitation of renewable energy resources in the country. Therefore, the generation of electricity at MMB port through solar PV will bring a major contribution to the power industry in Malawi.

ESCOM assumes the responsibility of Single Market Operator (SMO) and single market buyer, the utility purchases all the power produced by power generating entities like EGENCO, IPPs and other generators in the country then transmits and distributes it to both large and small customers respectively. In 2018, the national grid got connected to Zambia through a 33kV Chipata-Mchinji transmission power line importing 20MW of electricity (ESCOM, 2018). The project was in line with the East African Power Pool (EAPP) electricity trading arrangement.

ESCOM also owns, maintains and operates high voltage transmission networks and electrical plants which consists of 66kV, 132kV and 400kV transmission lines as well as medium and low voltage distribution networks which consists of 33kV and 11kV distribution lines which are stepped-down to 400/230V using distribution transformers for secondary distribution. The electricity is supplied to over 300,000 large and small customers who are further categorized as industrial, commercial, general and domestic customers inclusive of MMB port. Table 1 shows a summary of key institutions in the energy sector in Malawi.

Institution	Role
Ministry of Natural Resources, Energy and Mining (MNREM)	Energy legislation and policies. Responsible for all upstream energy activities such as exploration and ex-traction of fossil fuels and minerals, which may be used as sources of energy.
Malawi Energy Regulatory Authority (MERA)	Statutory corporation created under the Energy Reg-ulation Act, 2004, which mandates MERA to regulate all activities in the energy industry including licensing, approving tariffs, monitoring and enforcing compliance, developing standards etc.
Electricity Supply Corporation of Malawi (ESCOM)	State-owned power producing company; in control of transmission and distribution of electric power in the country. Used to be in charge of generation, but was unbundled as from 1/1/2017 as part of the energy reforms aimed at improving the efficiency of energy provision in the country.
Electricity Generation Company Ltd (EGENCO)	Following the reforms, EGENCO was established and will solely be responsible for electricity generation starting 1/1/2017
Malawi Electricity Generation Agency (MEGA)	The first licenced generator and distributor of electricity in the Mulanje region based on micro-hydro power.

Table 1: Key institutions and their roles in the Malawi's energy sector ("Renewable Energy Market", 2017).

2.5.2 POLICIES, LEGISLATION AND REGULATIONS

The electricity sector in Malawi is guided by the Energy Policy of 2003 and 2018, Electricity Act No. 22 of 2004, and the Energy Regulation Act No. 20 of 2004. The policy and energy laws encourage participation of the private sectors in electricity generation and distribution. The 2018 energy policy emphasises the importance of establishing regulatory framework that supports the energy policy in increasing universal access to reliable, effective, efficient, affordable, secure, sustainable and modern energy for all Malawians by 2030 (National Energy Policy, 2018). Following the introduction of the energy policy the governance of the energy sector has improved; impacts of safety, health and environment has been mitigated in the production and utilisation of energy.

2.6 ELECTRICITY GENERATION PLANTS IN MALAWI

All the hydro-power stations in Malawi are run of river system, six are cascaded along the Shire river and one is along the Wovwe River. This makes electricity supply unreliable since the generation relies on the water levels in the river which is negatively impacted by floods, droughts, aquatic weeds infestation and siltation (Kaunda & Mtalo, 2013). These problems at some point lower the water levels in the Shire river as a result inefficient electricity is generated which is insufficient to meet the high consumption demand.

Table 2 shows the location, capacity and year of completion of power generating stations in Malawi. Currently, out of 1,593.97MW installed capacity only 462.97MW is available of which 441.95MW is hydro-power as of August 2021. The capacity is projected to increase by 1,631MW by 2034 (EGENCO, 2021) as many plants awaits commissioning.

Table 2: Power stations in Malawi

Power station (PS)	Location	Capacity (MW)	Year of completed
Hydro-power stations			
Kapichira	Shire River	128	2000 & 2014
Nkula A	Shire River	35.1	1966
Nkula B	Shire River	120	1980, 1986 & 1992
Tedzani I	Shire River	20	1973
Tedzani II	Shire River	20	1977
Tedzani III	Shire River	62	1996
Tedzani IV	Shire River	19	May 2021
Wovwe	Shire River	4.35	1996
Mpatamanga	Wovwe river	350	2025 (Expected)
Songwe	Shire river	180	2022 (expected)
Kholombidzo	Shire river	200	2021 (Expected)

Solar power stations			
Kanzimbe	Salima district	60	2021 (expected)
NKhotakota	Nkhotakota district	21	2022 (expected)
Golomoti	Dedza district	20	2021 (expected)
Likoma & Chizumulu	Likoma & Chizumulu islands	1.3	2020
Thermal power station	**Type of fuel**		
Kam'mwamba	Coal-powered	300	2022 (Expected)
Mapanga in Blantyre	Standby-diesel-gensets	20	2019
Kanengo phase I	Standby-diesel-gensets	10	2019
Kanengo phase II	Standby-diesel-gensets	10	2019
Lilongwe A	Standby-diesel-gensets	5.4	2019
Luwinga in Mzuzu	Standby-diesel-gensets	6	2018
Likoma islands	Standby-diesel-gensets	1.168	2019
Chizumulu island	Standby-diesel-gensets	0.652	2019

Source: (EGENCO, 2021), compiled by (Author, 2021).

The electricity sector was initially dominated by almost 95% hydro-generated electricity (Kachaje et al., 2017), since the introduction of the flexible power market it has been reduced to 59% as shown in figure 7. Hydro-energy does not negatively affect the environment but the production of electricity is affected by the environmental degradation as it relies on rainfall. It is expected to continue to fall as it gets replaced with other RES. Although solar energy is available in abundance in Malawi only a small fraction (10%) is being utilised for electricity generation.

Promotion of solar energy technologies is a major initiative in curbing the country's energy demand and reducing cost of both production and purchase of electricity by power sellers and buyers respectively. Government incentives can also play a crucial role to encourage energy investors to invest in the country; unfortunately, there is no government incentives or soft loans for development of the renewable technologies in Malawi.

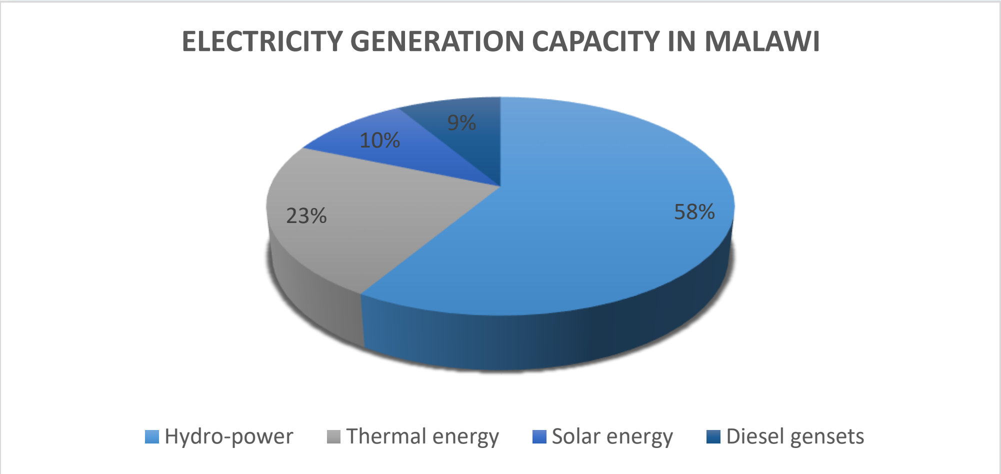


Fig 7: Summarised energy generation capacity in Malawi (Author, 2021).

The Government of Malawi (GoM) has put several initiatives in place in order to achieve power security viz: MAREP; United Nation Sustainable Development Goals (UN SDG7); Sustainable Energy for All (SE4All); purchase of 78 diesel-powered generators which boosted the national grid by 53.22MW according to the Cooperation Network for Renewable Energy in Malawi [CONREMA] (CONREMA, 2018).
The country uses diesel-powered generators and coal-fired plants though these initiatives are not environmentally friendly as they emit carbon to the atmosphere, affect the hydro-power generation. The country is a party to Paris Climate Agreement (accord), however its main concern is to find measures to deal with the energy crisis hence the use of fossil fuels and coal-fired power station. In this case, the electricity problem is solved in an unsustainable manner as the solution has created another problem, yet a permanent solution is found through the use of renewable energy resources.

2.7 SOLAR ENERGY GENERATION POTENTIAL IN MALAWI

Solar energy has the greatest potential to fill the energy gap in the country's energy sector. The country receives 8-12 hours of sunlight per day throughout the year which can be harnessed through solar PV or photo-thermal applications to generate 244W/m^2 /day or 2133 kWh/m^2/year (Taulo et al., 2015) throughout the country. This light intensity would allow photovoltaic and solar systems to perform effectively (Gamula, 2012) for instance a 60MW solar power project at Kanzimbe power station in Salima ("Early Warning System", 2020) will boost the national grid. Many other solar generating stations can be installed along the shores of lake Malawi, Monkey-Bay inclusive since the area receive a lot of sunlight than many other parts of the country.

Malawi needs new capacity to cope with the fast growing energy demand although there seem to be few prospects for progress in utilization of solar energy in the country. Therefore, further research is needed to determine the viability of solar energy at MMB port so as to supplement the national grid by creating this micro-grid which will not only supply the port but also several local communities near the port. Monkey-Bay is an ideal site for this research as it is along the shores of Lake Malawi which is unbearably hot with strong solar irradiation. It is time to use renewable power sources which neither pollute the environment nor cause healthy hazards in humans. Solar energy is environmentally sustainable and in the long run economically viable as it can reduce all carbon emissions, solve environmental issues hence create a clean environment. With the use of solar energy at Monkey Bay Maritime Base port, the country will be able to meet its emission target under the Paris climate deal (Tan, 2019).

CHAPTER 3

3.0 METHODOLOGY

3.1 METHODS USED IN THE RESEARCH

Both qualitative and quantitative methods (Mixed methods technique) were used to collect the required data more specifically through Systematic Literature Review (SLR) where articles, books, journals, periodicals, reports and databases were evaluated. For example, quantitative data of solar irradiation at Monkey-Bay was retrieved from Global Solar Atlas database, this information plus SLR were used to calculate the sunlight intensity that Monkey-Bay receives and its viability for solar energy production.

Then, in order to assess the feasibility of solar energy at MMB port, Levelised Cost of Electricity (LCOE) calculator was used to analyse the viability of the solar project, to investigate the profitability of the technology if it can break-even or not. Then sensitivity analysis was conducted through Monte Carlo Simulation using Crystal ball software in excel format (spreadsheet file) in order to determine the minimum price, the electricity will be purchased.

This was followed by SWOT analysis to identify threats, weaknesses, opportunities and strengths that may be explored in implementing solar energy as a cost-effective measure to reduce emissions from ships. Benchmarking analysis was used to analyse the best solar energy practices from ports of Rotterdam, Jurong and Long Beach. This created a big picture that helped the researcher to draw innovative recommendations on energy consumption, planning and management for consideration by MMB port authority.

In this chapter, three crucial parameters will be examined so as to evaluate the economic viability of solar PV technology at the port namely: Capital Expenditure (CAPEX), Operating Expenses (OPEX) and fuel cost of the asset. These are systematically considered using a common metrics called LCOE.

3.2 CAPITAL EXPENDITURE (CAPEX)

CAPEX is the total cost of purchasing, developing and installing any physical assets (Kenton, 2019). CAPEX for solar power plant include the purchase and installation of Solar panels, batteries, inverter, charge controllers, Supporting structures, copper cables and accessories, testing, and civil works; anyhow, it does not include grid-connection charges. CAPEX is shown on the company's balance sheet as an investment rather than on its income statement as an expenditure. The current global weighted-average total installation cost/CAPEX is US$883/kW for a utility-scale solar Photovoltaic (IRENA, 2021). Currently, the government of Malawi does not provide any incentives or subsidies for investing in renewable projects.

3.3 OPERATIONAL EXPENDITURES (OPEX)

Also known as Operations and Maintenance cost (O&M), *" is the total annual expenditure from the first year of the project's operations given per unit of installed capacity terms"* ("World Energy Council", 2013), it includes insurance and asset management. OPEX varies depending on whether the solar PV project was commissioned in Organisation of Economic Co-operation and Development (OECD) countries or not; if commissioned in non-OECD countries like Malawi OPEX is US$9.3/kW/year as of 2020 (IRENA, 2021).

3.4 FUEL COST AND CAPACITY FACTOR (CF)

Fuel cost in solar PV technology is not applicable since the technology uses sunlight as its fuel which is free of charge, therefore the cost is US$0/kWh to harness sunlight except for CAPEX and OPEX as discussed above. However, an element of capacity factor or load factor has to be considered.

"CF is a measure of how much energy is produced by a plant compared with its maximum output" National Renewable Energy Laboratory [NREL] (NREL, 2013). World Energy Council, (2013) defined CF as *"the ratio of the net megawatt hours of electricity generated in a given year to the electricity that could have been generated at continuous full-power operation"*. It is calculated by dividing the total amount of

energy the plant produced over a given period of time by the total amount of energy the plant would have produced if it ran at full capacity during that time. It is usually measured as a percentage. CF differs depending on the type and availability of fuel being used (sunlight, wind, water, biomass) and the design of power plant. The availability of solar energy depends on factors like seasonal changes, cloud cover and most importantly the daily rotation of the earth. The typical values of CF for renewables ranges between 15-33.9%, the current global CF for solar PV is 16% (IRENA, 2021).

3.5 LEVELISED COST OF ELECTRICITY (LCOE) FOR SOLAR PV

LCOE is defined as an economic assessment of the total cost of building and operating a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime. In other words, it is the price that must be received per unit of output as payment for producing power in order to reach a specified financial return or simply the price that project must earn per megawatt hour (MWh) in order to break even (World Energy Council, 2013). *"The LCOE can also be regarded as the minimum cost at which electricity must be sold in order to achieve break-even over the lifetime of the project"* (Lai & McCulloch, 2017). The electricity price above LCOE will yield a greater return on capital (profit) while a price below it will yield lower return on capital (loss). LCOE will decrease with an increase in energy production of the system, however, the amount of energy generated decreases with time. The smaller the LCOE the better the investment therefore, invest in projects that offers a lower LCOE.

LCOE allows financial analysts and port decision markers to compare different energy producing technologies like solar, wind and natural gas regardless of their different lifespans, risks, return, capital costs, capacities and size of the project (Lai & McCulloch, 2017). The comparison can be done through Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) using Crystal Ball software.

Port energy planners uses LCOE to assess the feasibility of a renewable energy technology to determine the economic viability of a power generation asset over its lifespan. The values of LCOE varies depending on the location and financing cost of the project which differs by region (Lai & McCulloch, 2017). Variation of irradiance strength has a direct effect on energy output for instance, more solar power is generated in hotter regions with long daylight hours and vice versa for cold regions around the globe.

3.6 CALCULATION OF LCOE OF SOLAR PV TECHNOLOGY

Mathematically, LCOE of solar energy is calculated by dividing the Net present Value (NPV) of the total costs of installing and operating a power generating plant over its lifetime by estimated total amount of electricity generated by the system over its lifetime (Sinaga et al., 2019). In other words, LCOE measures energy consumption of the system based on NPV. Simply put, the total sum of costs of initial investment, fuel, O&M costs associated with energy production divided by the total sum of energy produced over the lifetime of the asset (Lotfi et al., 2016), LCOE is calculated using equations (1)-(3):

$$\text{LCOE} = \frac{\text{Total Lifecycle cost (\$)}}{\text{Total Lifetime energy production (kWh)}} \qquad (1)$$

$$\text{LCOE} = \frac{\text{Capital cost (\$) + Operational cost (\$/year) + fuel cost (\$/year)}}{\text{Net annual energy production (MWh/year)}} \qquad (2)$$

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (3)$$

Where:

I_t = Initial cost of Investment expenditures in the year t (Including financing)

M_t = Maintenance and operations (O&M) expenditures in the year t

F_t = Fuel expenditures in the year t (if applicable i.e no fuel costs for solar PV)

E_t = Total Electricity generation of solar PV in the year t

r = Discount rate

n = Economic Lifetime of the system

The total costs associated with the project are I_t, M_t and F_t while E_t is the total energy output of power-generating assets; r and n are two important factors that must also be considered in the equation. Total electricity generation $E_t = E_p (1 - d)^t$. E_p is the effective energy production of PV in the year t, d is a degradation factor of the PV modules. Note also that I_t is a one-off payment, it should not be discounted and must be taken out of the summation.

The PPA is another important element that is used in the calculation of LCOE for renewable technologies. Basically, before a solar energy project is developed sales agreements and electricity distribution must be reached to ascertain the end-user of electricity generated by that system.

3.7 POWER PURCHASE AGREEMENT (PPA)

PPA is a contractual agreement between energy buyers and sellers who come together and agree to buy and sell an amount of energy which is or will be generated by a renewable asset for a given period of time. A PPA is also a financial agreement where the developer arrange for the design permitting financing and installation of energy system on a customer's property at a little cost. It is used in the absence of government incentives or subsidies as financial security proof to lending institutions like banks that a renewable asset or an investment has found a long-term buyer at a fixed price. The PPA purchase price is important to determine whether the PPA is profitable or not. For the investors, if a PPA is higher than LCOE then the project is viable, go for the project because it is profitable. In short, a PPA rate is the price paid for purchasing a unit of energy ($/kWh).

3.8 LCOE CALCULATION FOR SOLAR PV ENERGY AT MMB PORT USING LCOE CALCULATOR

The LCOE calculator calculates the constant average annual price that the renewable power plant attains over its lifetime that achieves the target return on investment after break even or after covering all fixed and variable cash costs. In other words, it calculates how much money you need to invest in a project in order to produce a unit of energy expressed in ($/kWh). It calculates the minimum price at which energy must be sold using equations (1)-(3).

The actual LCOE calculation is discussed in chapter 5. Before tackling the energy scenario at MMB port, lets investigate three leading ports from three different continents which has shown remarkable success upon solar PV installation for their port usage.

CHAPTER 4

4.0 BEST APPLICATION PRACTICES OF SOLAR POWER SUPPLY TECHNOLOGY IN PORTS

4.1 DISCUSSION AND ANALYSIS

In order to encourage MMB port authority to adopt solar power for cold ironing, it is of great importance to benchmark and understand what other ports have already done and is working perfectly for them. The use of solar energy has been implemented in various ports around the world mostly in Europe, USA and Asia. Nevertheless, in this research only three ports are reviewed namely: ports of Rotterdam, Jurong and Long Beach as they have exhibited excellent strides towards solar energy with a remarkable reduction in GHG emissions. The strategies used by these selected ports has proven that the use of solar technology is not only sustainable but also cost-effective with zero-negative externalities on port communities. Consequently, a benchmark has been created in which MMB port will work on towards implementing the technology at the port.

4.2 PORT OF ROTTERDAM IN NETHERLANDS, EUROPE

Established in the year 1283, the 42km port of Rotterdam is the largest port in Europe ("World Port Source", n.d). It is the busiest port that safely and efficiently facilitates over 1.17million TEU per month of mostly imported raw materials. It is at a spearhead of marine innovation to become the smartest port in the world.

In 2016, port of Rotterdam installed 11,000 solar panels on the company's buildings rooftops at the "cool port" with an installed capacity of 2.93 Megawatts-peak (MWp) that produces a total power output of 2,637MWh/year, a consumption equivalent to 737 households (Marasi News, 2016) as shown in figure 8. A similar project was conducted at Frigo Care's rooftop by ZEN where 3,100 solar panels were fitted that generates 750,000kWh of electricity per year, enough consumption for 250 households. The port also invested in several other solar projects that increased electricity production to more than 3GWh, it aims at producing more than 1,000GWh by 2030 so as to reduce the port's carbon footprint. The port uses advanced technology to produce affordable, reliable and sustainable greener energy supply not only for the port but also for North-West Europe.

Figure 8: Solar panels on the rooftop of the warehouse at Port of Rotterdam (Marasi News, 2016).

The port also depends on three coal-fired power stations, three natural gas-fired power stations, one biomass power station to produce the required energy. High energy efficiency is also achieved through use and reuse of steam and heat from the energy industry. It is gradually moving away from generating energy using unsustainable methods hence the use of the most sustainable renewable energy sources like solar and a 200 MW wind power plant. There is greatest potential of generating solar power if rooftops in ports are put to good use especially in hottest days where there is a need for products to be kept cool i.e electricity generated by solar in hottest days is consumed immediately to cool products like fish and fruits in the warehouses. Again, on the hottest day, the port can run on solar power only, for the whole day and the excess electricity is supplied to the Netherlands' grid.

The installation of the green energy system is a major sustainability strategy in environmental protection. The initiative was undertaken in partnership with Dutch renewable energy company Zon Exploitatie Nederland (ZEN) which worked in close cooperation with the Port of Rotterdam Authority. This partnership has enabled the port to reduce carbon dioxide emissions by 325 tonnes per year.

4.3 JURONG PORT IN SINGAPORE, ASIA

Established in 1965, 5.6Km long, Jurong Port is a major international multi-purpose port operator that handles both containerised and general bulk cargoes facilitating over 15,000 vessels annually.

In 2016, the port commissioned world's largest port-based solar energy generation facility with the capacity of 9.65MWp which powers its onshore operations in the most sustainable manner. An estimate of more than 12 million kilowatt hour (kWh) of solar energy is generated per year offsetting more than 60% of the port's electricity needs and the excess electricity is sold to Singapore's grid (Bantillo, 2016) see figure 9. The panels were installed on a 95,000m² of its warehouse rooftop space, the whole project costed US$30 million.

Figure 9: Solar panels at Jurong port (Bantillo, 2016).

The use of solar power at Jurong port reduces 5,200 tonnes of carbon emissions per year. The shift to this clean energy source could act as a model for other ports and heavy industries that are looking forward to sustainable energy consumption in order to reduce carbon footprint while saving electricity costs. Apart from transitioning to environmentally sustainable renewable energy, the port also restructured its cargo storage and despatch chain to cut down on unnecessary movements so as to reduce energy consumption. The use of solar power at the port also reduces load on the national grid for instance, 70% of Singapore's energy is used by industries and commercial sectors, so with the use of solar power at the port more energy will be redirected to residential homes and small businesses that will boost the country's economy.

4.4 PORT OF LONG BEACH IN CALIFORNIA, USA

Established in 1911 and covering 13Km^2 of land, the 40Km port of Long Beach is one of the world's busiest port and the second busiest container seaport in the USA that has the capacity to handle over 1.3 million 20-foot container units (TEUs) and over $200 billion worth of cargo each year (Gerdes, 2020).

In an effort to contribute to a sustainable environment as well as adhere to Green port policy and San Pedro Bay Clean Ports Clean Air Action Plan, in 2016, the port installed 3,290 PV solar modules on its twelve carport structures at two sites of container terminal E (Mitsubishi Electric, 2016) as shown in figure 10. The system has the potential of generating 904.75kW photovoltaic, approximately 1,547MWh of energy per year (Richardson, 2016).

Figure 10: Solar panels on carport of Long Beach ("Mitsubishi Electric", 2016).
The $1.31billion solar project at the port has contributed in offsetting 1,127 tons of CO_2 annually from polluting the environment ("Port technology International", 2016). This project has made Long Beach Container Terminal (LBCT) the greenest, most technologically advanced and the first-near zero emission container terminal on the planet. Employment of over 14,000 permanent employees in southern California and 1,000 temporary employees in construction-related-jobs are other benefits that came along with the solar PV project.

The solar panels made by Mitsubishi Electric were selected by LBCT based on their durability and ability to resist corrosion since the air at the port has high salt content due to salty seawater ("Mitsubishi Electric", 2016), salts accelerate the corrosion process when in contact with metals like aluminium the product which is used in manufacturing the frames of solar panels. LBCT ventured into a 25-years Power Purchase Agreement (PPA) with SoCore Energy a subsidiary of Edison Energy which paid the installation and development companies i.e Rosendin Electric and PFMG solar respectively.

The installation of a 300kW solar project at the port is expected to commission in 2022 (Crowell, 2018; Gerdes, 2020), this will help the port to achieve its goal of operating with zero-emissions.

4.5 BENCH MARKING ANALYSIS

From the three ports we learn that through the implementation of solar energy technology both for cold ironing and other port usages, not only was the energy consumption reduced but also a huge amount of carbon was off-setted portraying a great success in solar investment. Also, a remarkable improvement in power market values as witnessed by supplying the extra generated power to the national grid plus the ports became smarter and greener.

The motivation to invest in solar projects emanated from a policy, regulation or voluntary port's initiative to reduce energy consumption from non-renewable based energy sources. It can be fully funded by the government or the port itself or a solar company can use port's facilities to install panels and a power purchase agreement is made so that port purchases power from them and pay as per their usage. All these are as summarised in table 3.

Table 3: Summary of common factors/parameters in three ports (Author, 2021).

Factors in common	Port of Rotterdam	Jurong port	Port of Long Beach
Where was the PV modules installed	Warehouse rooftops (more than 14,100 solar panels)	Warehouse rooftops (95,000m²)	12 Carport structures
What motivated the port to invest in the project	Green port initiative	To act as a model in sustainability	Green port policy
How much CO2 emissions were off-setted per year	325 tonnes	5,200 tonnes	1,127 tons
Method of funding	PPA with ZEN (partnership)	Self funded (port's initiative)	Government funded
How much the project costed	-	US$30 million	US$1.31 billion

4.6 SWOT ANALYSIS

This section analyses Strengths, Weaknesses, Opportunities and Threats (SWOT) on adoption of solar power in ports as indicated in table 4. Lessons learnt from this analytical evaluation are a benchmarking analysis that helped the researcher to investigate and assess the viability of adopting the same strategies to install solar PV technology at MMB port in Malawi for electricity generation to be used for cold ironing by berthed ships that calls the port. If all ports adopt similar or different but renewable initiatives globally then environmental sustainability can be achieved.

Table 4: SWOT analysis on the Implementation of Solar PV technology

Strengths	**Weaknesses**
✧ Solar energy is a reliable RES that produces clean energy and its sources can never be depleted, the sun will stick around for at least a billion more years. ✧ More sustainable and Environmentally friendly. Installation of solar system mitigates carbon emissions and negative externalities leading to clean environment as well as better health of crew and local communities due to absence of combustion of fossil fuel. ✧ Ease of production. Solar panels can be installed almost everywhere. ✧ Low budget allocation for O&M costs. ✧ Versatile. Solar energy can be applied in various applications like Photovoltaic. ✧ Mitigates noise pollution in such a way that solar panels have no moving parts and that auxiliary engines of berthed vessels are	✧ High initial cost of purchase and installation of the system. This can be solved through provision of soft loans, government incentives and subsidy/tax exemption. ✧ Intermittency. The technology is weather dependent. There is need for large batteries to store energy and/or connecting to the national grid. ✧ Solar panels are inefficient. ✧ Solar panels occupies a lot of space and may cause land degradation or biodiversity loss . A large solar PV may need 3.5-10 acres of land per Megawatt of electricity produced (Johnston, 2021). It is important to ensure that the natural habitats are not disturbed by installing the facility on a barren land. ✧ Emissions are reduced from berthed ships only and not during transit. Installing panels on the

switched-off hence noiseless.	ship which may add unnecessary weight. ✧ Limited availability of materials for the solar system on the market. This can be dealt with through recycling of PV materials and use of advance nanotechnology to boost solar-cell efficiency and increase power supply.
Opportunities ✧ Creation of new business opportunities, for instance, landowners can rent/lease their unused land for solar farms and get income. ✧ It creates employment opportunities and boosts the country's economies as it reduces the country's dependence on foreign fossil fuels. ✧ Due to increased volatility in conventional fuels price and its environmental concerns, solar energy is a better alternative that could reduce ships' operational costs. ✧ Possibility of energy independence and security. ✧ The port can be benchmarked setting an example for other ports to adopt solar energy for OPS. ✧ Advancement in technology has led to a decrease in global prices of solar system thus reduced electricity cost. ✧ Attracts more investors to invest in a country with access to sufficient and reliable electricity supply.	**Threats** ✧ Health risks. Disposal of lethal waste from solar panels (chromium, lead and cadmium) are a danger to the environment. In addition, burning of panels to reclaim copper, produces poisonous smoke which may cause cancer and birth deformities in infants if inhaled. ✧ Solar photovoltaic technology emits 12g/kWh of carbon footprint during its entire lifecycle (Guangul & Chala, 2020). Carbon is produced during extraction of raw materials, transportation, manufacturing and recycling. ✧ Acquaintance with fossil fuels. Since conventional fuels has been in use since time in memorial, its infrastructures are well established globally which creates a barrier to coexist with solar, a new technology with high initial costs. ✧ Economical risks in terms of payback period which is usually long-term. Ports in cold regions are not willing to take up the technology due to few hours of sunlight making the technology available in very few ports globally.

	✧ Electricity generated by auxiliary engines is cheaper as compared to that of solar powered OPS. ✧ Handling of high voltage by less skilled crew members may give rise to safety issues. ✧ Potential land disputes between investors and landowners (locals).

Sourced: (Author, 2021)

Port authority should aim at maximizing strength of the technology in order to make the most use of the presented opportunities while working on the weaknesses and threats. Advancement in other technologies like electric vehicles and battery powered vessels is anticipated to increase demand of OPS to charge their batteries while at berth.

CHAPTER 5

5.0 LCOE ANALYSIS AND APPLICATION OF SOLAR PV ENERGY AT MONKEY BAY MARITIME BASE (MMB) PORT IN MALAWI (CASE STUDY)

5.1 BACKGROUND INFORMATION OF MMB PORT

MMB port is located at -14.069981°,034.921417° in Mangochi district in Malawi as shown in figure 11. The port has a high potential for solar power given its high solar irradiation, according to information retrieved from "Global solar Atlas" (2021) database, Monkey-Bay receives 2161.1kWh/m^2/year of global solar irradiation on a horizontal surface an average direct solar power of 246.7W/m^2 at any given time as shown in table 5. GHI is the averaged insolation on horizontal surface, GTI is the annual averaged insolation on equator pointed surface i.e. tilted at latitude angle.

Figure 11: Location of Monkey-Bay source: (google maps, 2021)

Table 5: Solar irradiation for Monkey Bay ("Global solar Atlas", 2021)

Description	**Per day**	**Per year**
Specific photovoltaic power output (PV_{OUT} specific)	4.843kWh/kWp	1767.7kWh/kWp
Direct Normal Irradiation (DNI)	5.347kWh/m^2	1947.6kWh/m^2
Global Horizontal Irradiation (GHI)	5.938kWh/m^2	2161.1kWh/m^2
Diffuse Horizontal Irradiation (DIF)	2.025kWh/m^2	739.2kWh/m^2
Global Tilted Irradiation at optimum angle (GTI opta)	6.157kWh/m^2	2237.8kWh/m^2
Optimum tilt of PV modules (OPTA)	18/0°	18/0°
Air temperature (T°C)	25.1°C	25.1°C
Terrain elevation (ELE)	476m	476m

Source: (Author, 2021)

5.1.2 THE PROPOSED SOLAR POWER GENERATION AT MMB PORT

MMB port has single-level buildings which are surrounded by tall trees which shade the rooftops of the buildings most hours of the day rendering rooftops not an ideal place for solar PV installation as the panels will not harness sunlight to their maximum potential. Instead, arrays of solar PV modules will be ground mounted so as to generate power for the port and surrounding communities as the excess will be supplied to the national grid.

If the solar plant is fully utilised, there will be a huge reduction in GHG emissions as well as enormous cost savings due to reduced energy bills. In that regard, the following sections of this chapter calculates the port current energy consumption along with the required number and sizes of solar panels as well as the area to accommodate the solar PV arrays that will generate electricity, enough for the port under study.

5.1.3 TOTAL ENERGY CONSUMPTION AT MMB PORT

In 2020, MMB port spent $3,075.84 (MK2,500,000) every month for the whole year on electricity bills, this accumulated to $36,910.02 (MK30,000,000.00) at the end of that year. The current cost of electricity for a general single-phase supply like that of MMB port is $0.14/kWh (MK117.30) (ESCOM, 2021). Therefore, the total monthly electricity consumption at MMB port is 21,312.87kWh (i.e MK2,500,000/MK117.30/kWh), this electricity is used for all port operations that include lighting, cold ironing to berthed vessels and powering office buildings, machinery and all other facilities essential to port operations as indicated below:

- Dockyard - marine afloat, boat workshop, gear and equipment workshop, electro-mechanical workshop, boat warehouse, rubber boats shed and Security lights.
- Administration block - Malawi Maritime Forces (MMF) office buildings.

5.1.4 CALCULATION OF REQUIRED NUMBER OF SOLAR PANELS

To completely offset electricity bills at MMB port, it is crucial to know the number of solar panels that must be installed. How many panels to install depends on the average monthly electricity consumption which is 21,312.87kWh as calculated above.

The average monthly solar power generation at Monkey-Bay is 180.1kWh (i.e. 2161.1kWh/12 months) as calculated using data retrieved from "Global solar Atlas" (2021) database, the country receives 4-12hours of sunlight all-year-round (Taulo et al., 2015). Then, solar panel requirement (kW) is calculated as shown below:

$$\text{Solar panel requirement (kW)} = \frac{\text{Average monthly power consumption}}{\text{Average monthly solar power generation}}$$

$$= \frac{21{,}312.87\text{kWh}}{180.1\text{kWh}}$$

= 118.34kW of solar panels

Then, the number of solar panels is calculated by dividing the kilowatt (kW) solar requirement by the wattage of one solar panel (Patel, 2019). If a 330W monocrystalline solar PV module is used then the number of solar panels is calculated as shown below:

$$\text{number of solar panels} = \frac{\text{Solar panel requirement (kW)}}{\text{Wattage of one solar panel}}$$

$$= \frac{118340W}{330W}$$

= 359 solar PV panels

In other words, MMB port needs 118.34kW of solar panels or 359 panels of $330W_p$ each to offset 90% of its electricity bill.

5.1.5 CALCULATION OF AREA REQUIRED TO INSTALL SOLAR PANELS

The total area required depends on the size of one solar panel and the total number of solar panels to be installed. For example, A 22.5kg 72 cell STC Monocrystalline solar PV module of JKM330M-72 Jinko $330W_p$ with dimensions of 1956×992×40mm (Jinko solar, 2021). This single panel has a total area of $2m^2$, calculated by multiplying length with breadth in metres.

The total area required for solar panels installation is calculated by multiplying the total number of solar panels by area of one panel. In this case, the total area required is $717m^2$ (i.e 359 panels* $2m^2$), this is the actual area that 359 solar panels will be installed back to back or side by side. However, extra walking space is required between rows and columns of arrays to provide access during cleaning, troubleshooting and maintenance when need arises.

Extra space is also required for inverters, cabling and storage batteries; therefore, an estimated area of $825m^2$ will be required (at least 15% extra space). Therefore, a site with a total surface area of $825m^2$ will be utilised for ground mounting of solar PV modules to generate electricity of 21,312.87kWh to meet the monthly port consumption and supply the excess to the national grid especially during the peak hours when it generates more than what the port needs. The site has an estimated output of 255,754.44kWh/year.

5.1.6 TYPE AND SIZES OF SOLAR PANELS

A solar panel is made up of electronic devices called solar cells or Photovoltaic (PV) cells that converts sunlight in the form of photons directly into electricity in the form of voltage hence the name photovoltaic (Bodell & Chiriboga, 2018). The size of a solar panel depends on the number of columns and rows that form a PV module. The standard size of a single solar cell is 156mm x 156mm (Patel, 2019), two standard dimension of a PV module are 60 cell solar panel (6 X 10mm), weighs 19kg and 72 cell solar panel (6 X 12mm), weighs 25kg. When Several PV modules are connected together they form an array of Photovoltaics which generate electricity enough to power a port, buildings, electric vehicles and many more. The larger the size of a solar panel the more sunlight it absorbs and convert to useful electricity, the heavier it weighs the higher it costs.

The most commonly used types of solar panels are monocrystalline, polycrystalline and amorphous thin-film solar panels. MMB port will use monocrystalline panels because they have more desirable characteristics as compared to other types of panels. Monocrystalline has a black surface colour since it is made from pure silicon and has the highest efficiency of 15-20% (Geotherm, 2021), or 14-22.8% (Bodell & Chiriboga, 2018) hence space efficient. They perform well at low-light conditions and in high heat environments, they are less affected by high temperatures making them more efficient in warm weather like that of Monkey Bay. The level of electricity production in solar cells falls with increase in temperature, this degradation is less severe in monocrystalline as compared to polycrystalline solar panels.

They have highest power output and a long lifespan of more than the warranted 25years, this means that after the warrant expires, the monocrystalline will continue to generate a notable amount of electricity. If a monocrystalline is in unison with Lithium batteries which has a lifespan of 10-15years, an inverter with a lifespan of 10-20years if well maintained (Eales et al., 2020) then you are assured of yielding more output throughout the projects useful life.

On the other hand, monocrystalline modules are most expensive and its manufacturing process is more wasteful as compared to other types of solar panels (Unbound solar, 2020), This is so because silicon wafers are made by cutting four sides out of cylindrical shaped silicon ingots. Another drawback is that high temperature coefficient decreases efficiency of cells with time.

5.2 SOLAR ENERGY APPLICATIONS

There are three main applications areas of solar energy namely Photovoltaic, thermal and hydro:

- ✧ Photovoltaic (PV) systems, converts sunlight directly into electrical power by means of PV cells made of semiconductor materials. This application befits what MMB port needs, hence the implication of solar PV throughout this thesis.
- ✧ Concentrating Solar thermal Power (CSP) systems, these use mirrors to reflect then concentrate sunlight into receivers that collect solar energy to heat fluids that creates steam that is then used to drive a turbine and generate electricity or stored in batteries for later use. It is used primarily in very large power plants. A CSP plant can be equipped with molten salts to store heat way after the sunset (RENA,2021).
- ✧ Solar water heating systems contain a solar collector that faces the sun collects its energy to heat a working fluid that in-turn heats water or directly heats the water. Transpired solar collectors (solar walls) use solar energy to preheat ventilation air for a building

5.3 FACTORS TO CONSIDER WHEN SELECTINGING A SITE FOR SOLAR PV INSTALLATION

Solar PV panels works to their full potential and produce the maximum output if they are installed correctly. Numerous factors affect applicability and performance of solar PV panels in maritime applications. When selecting the site for solar project consider the following:

- **Shading.** Solar panels must be installed in an open space away from shadows to absorb maximum sunlight. An estimated 5-25% energy loss per year would result due to partial shading depending on site location (Bodell & Chiriboga, 2018).
- **Snow, dust and dirty.** Thick layer of snow, dust and other debris prevents rays of the sun from hitting the solar panels hence little or no electricity is generated. Dust can also change the inclination angle of PV modules reducing the output and increasing annual energy losses. Cell degradation also reduces the economic life of solar panels as cell efficiency reduces with time. Losses can be prevented by continuous cleaning of modules of which rain water would do the magic and bring the modules to their initial performance.
- **Inclination angle from the ground.** The earth changes position in summer and winter, choose the best angle that will give the maximum electricity generation throughout the year. Alternatively, use sun tracker system which follows the sun and gives maximum electricity generation, however, it is an expensive technology.
- **Orientation of the solar panel.** The sun approximately rises in the East and sets in the West with variation to the North and South of the equator depending on the time of the year. It is also biased towards the equator which makes Solar PV that faces the equator to convert most of the incoming solar radiation into electricity. Therefore, the best option is to orient solar PV panels towards the equator to get the maximum sunlight for instance, countries which fall in Northern hemisphere like India and Canada

their solar panels should be facing the South while those in the southern hemisphere like Malawi and Australia should be facing the north.

- **Technical specifications** of the module in terms of panel size/type, the humidity and the temperature it can withstand, module mismatch and its efficiency (Bodell & Chiriboga, 2018). These and cost of panels vary depending on location, availability and strength of solar irradiation, that is to say, larger systems are required in less sunny locations to generate the same amount of energy that smaller systems in sunny locations can generate.
- **Land tenure and the customer.** Investment deals need to be signed on a long-term basis to allow investors recover their returns. PPA must be reached before a solar project is developed to determine the end-users of the generated electricity. Knowing the beneficiaries of the project would encourage the government to issue incentives or motivate the banks to give investors loan.
- **Social aspects.** Consider the involvement of local communities as they are the ones to provide land for solar farm as well as potential end-users.The site should be at least 500m from the urban or rural residential areas to reduce the impacts on population growth.
- **Economical aspects.** Generally, the investment cost is higher in developing countries than in developed ones, due to underdeveloped or unavailability of supporting infrastructures like roads/rail, transmission lines plus incompetent labour force that involves bringing engineers from overseas. The site must not be more than 3km from the existing transmission lines if it is to be connected on-grid so as to save costs.
- **Environmental aspects.** Noise that would emerge during construction and maintenance of solar site plus chemical pollution (used during cleaning of panels) may affect locals, destroy habitats of sensitive species of birds and wildlife. Animals may suffer from displacement and relocation affecting their breeding, nesting grounds, foraging routines and gradually some species may loose interest and abandon the area. For example, 144 desert

tortoises were displaced at Mojave desert during the construction of Ivanpah Solar Farm in Nevada and California (Lofthouse et al., n.d).

- **Political aspect**. States must establish clear policies and regulatory boundaries must be established. If land of farmers is used, proper compensation must be facilitated in form of cash or another equal land in another region/area. Therefore, rehabilitation and resettlement must be handled amicably.

5.4 IMPLEMENTATION OF SOLAR ENERGY AT MMB PORT IN MALAWI

LCOE is a benchmarking tool which is highly sensitive to the assumptions made, more especially when predicting many years into the future. Hence, when used in sensitivity analysis like Monte Carlo Simulation (MCS) to consider a policy or a renewable project to be adopted, assumptions and forecast should be as accurate as possible. MCS technique is used in this research paper to analyse sensitivity of LCOE and PPA of a solar PV project at Monkey Bay.

5.4.1 CASE STUDY SCENARIO

Statistics for calculating LCOE of solar PV system for MMB is based on systematic literature review and energy consumption of the port in question. Assumptions are as summarised in the table 6.

System size is the power that the system can produce per given time, it was calculated by multiplying power of solar panel requirement (118.34kW) by number of solar panels (359panels). First year Production was calculated by multiplying system size by 24hours by 365days (i.e 42,484.06 kWh*24*365). Total initial system cost was calculated by multiplying system size by 883$/kWh (i.e 42,484.06 kW *$883/kWh) while first year O&M Cost was calculated by multiplying system size by 9.3$/kWh (i.e 42,484.06 kW*9.3$/kW) as given by (IRENA, 2021). The energy production produced by the system is expected to decrease in value (annual degradation rate of silicon-based panels) by 0.5%. Lastly, O&M costs will increase by 3% annually (PPA escalator).

Table 6: Assumptions used in LCOE calculation for Solar PV at MMB port

- ✧ Year of Commencement of Production - 2024 (the system will take 2years to build from 2022)
- ✧ Assumed lifespan of PV panels - 25years
- ✧ PPA escalator - 3%
- ✧ Annual degradation - 5%
- ✧ Currency used in calculation - USD ($)
- ✧ The exchange rate is US$1 equivalent to MK812.79 (Malawi Kwacha) as of 13 August 2021.
- ✧ System size (kW-DC) = 42,484.06 kW
- ✧ First year Production in (kWh) = 372,160,365.60kWh
- ✧ Total initial system cost ($/kWh) = $37,513,424.98
- ✧ First year Operation & Maintenance Cost ($/kilowatt) = $395,101.76
- ✧ Solar PV installation cost ($/kilowatt) = $883
- ✧ Operation & Maintenance Cost ($/kilowatt) = $9.3
- ✧ Fuel cost = $0
- ✧ Government incentives = $0
- ✧ Total electricity bills = $36, 910.02/year (MK30,000,000.00/yr)

Source: (Author, 2021).

5.5 FINDINGS OF LCOE CALCULATION AT MMB PORT

Refer to excel file in appendix I which shows detailed results of LCOE calculation using table 6 variables. The LCOE calculation results shows that after 25years the PPA (0.13742$/kWh) is greater than LCOE (0.00965$/kWh), this means that the solar project at MMB port is profitable. It is a viable and feasible option, the investor should invest in this project as it will break even. It is crucial to also note that more energy is produced during the early years of the system, however, determining energy output depends on assumed degradation rate of the solar PV system for instance between 0.2 to 1% per year for silicon Photovoltaics modules (Branker et al., 2011). Although panels degrades with time, Module encapsulation protects them from oxidation, moisture and can endure mechanical loads like hail, wind and snow.

Solar energy is a viable option to replace conventional energy sources in such a way that it is clean, limitless, free and its sources will never be depleted. Installation of more solar panels so as to generate more electricity and increasing the solar cells efficiency (developing PV that converts more sunlight into useful electricity) are some of the many ways of increasing the viability of solar technology.

5.6 SENSITIVITY ANALYSIS USING MONTE CARLO SIMULATION (MCS)

This research paper continues to analyse the LCOE and PPA presented in appendix I using MCS. MCS is a powerful spreadsheet-based (excel) and Crystal Ball modeling tool that allows financial analysts, engineers, scientists and managers in different organisations at decision making-levels to understand, visualise and quantify the effects of risks and uncertainty in a Discounted Cash Flow (DCF) in order to quickly and effectively come up with well informed decisions before investing in a project. It analyses the sensitivity of Net Present Value (NPV) and other parameters of the project.

MCS begins with a deterministic spreadsheet model of the situation under study then Crystal Ball is used to add stochastic/probabilistic assumptions (inputs) and forecasts (outputs) where the most crucial sources of uncertainties are represented as shown in appendix I. Then you choose the number of trials like 10,000 then run the program, once the satisfactory results are achieved, a decision is made on whether to invest in such a project or not. If a model is poorly defined it will not produce the intended outcome. The simulation results are displayed in form of graphical and numerical summaries viz: forecast, overlay, trends, scatter and sensitivity charts as described in few paragraphs below:

5.6.1 FORECAST CHARTS

The forecast chart (bell-shaped curve) is the primary output, a histogram of NPV that maps the entire distribution of possible outcomes and estimate the probability of the project's success (i.e NPV>0) (Clark, Reed & Stephan, 2010). NPV is a method used to determine the current value of all future cash flows (negative and positive) generated by an investment over its entire life discounted to the present.

The simulation results at 10,000 trials show that at a certainty of 56.10%, LCOE will have a minimum price of $0.00875 and a maximum price of $0.00991 as shown in figure 12. Similarly, at a certainty of 64.41% the PPA will have a minimum price of $0.12953 and a maximum price of $0.15345 as shown in figure 13. These are the forecasted price of purchasing power that will be generated by the project during its 25years economic lifespan. These prices directs both the investor/seller and buyer of power to predict if the project will break even and give more profits during its useful lifespan or not and to the buyer if the offered price is reasonable or not. It can clearly be seen that PPA is higher than LCOE, this means that the project is feasible. Note that the final electricity price paid by consumers will be different from the cost of generation because of variation in generation technology and accepted bids.

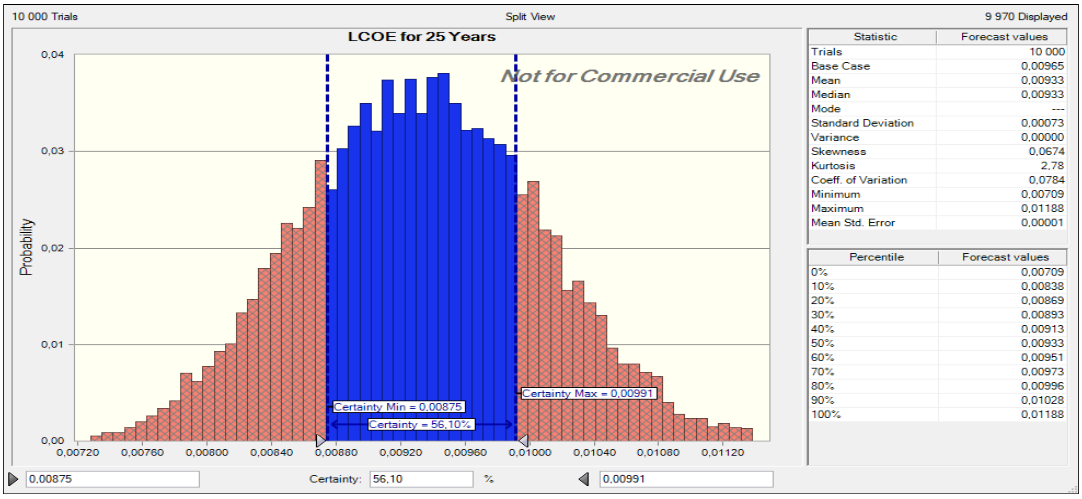


Figure 12: Forecasted LCOE price for 25years (Author, 2021).

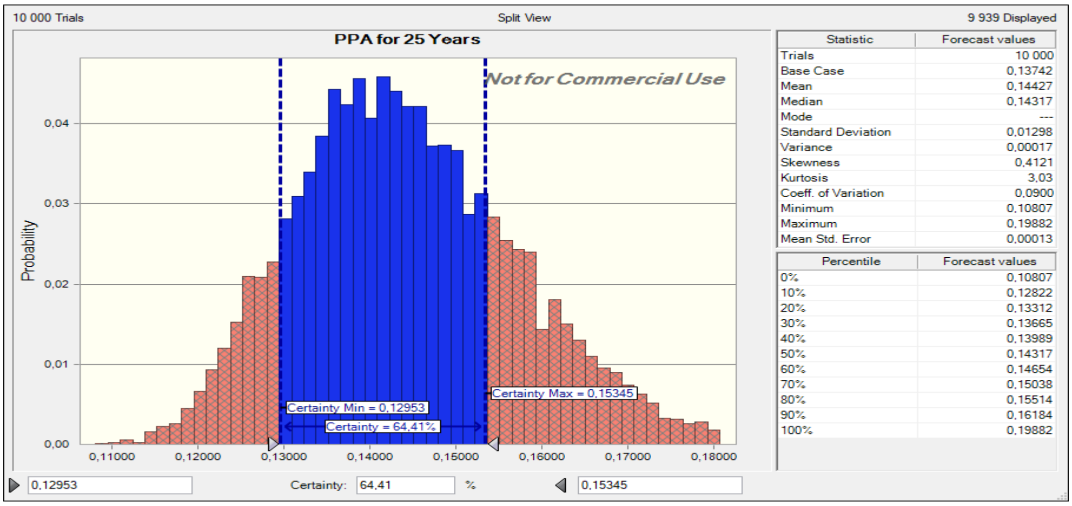


Figure 13: Forecasted PPA price for 25years (Author, 2021).

Also shown on the respective forecast charts are the statistics and percentiles. Statistics view provides numerical summaries of forecasts namely: trials, base case, mean, median, mode, standard deviation, variance, skewness, Kurtosis, coefficient of variability, minimum, maximum and mean standard error which are automatically computed by Crystal-Ball for instance the mean value of LCOE and PPA is 0.009333 and 0.14427 respectively. The Range is calculated by subtracting the Minimum from the Maximum statistical values (Charnes, 2007).

Percentiles view displays the forecast values that are just larger than the corresponding percent of all the values for instance, in figure 12, the 70th percentile LCOE for 25years is $0.00973. This insinuates that 70% of the forecast values were less than that amount, at the same time 30% were greater than that amount. Take note of the 50th percentile ($ 0.00933) value which is the same as that of the median in statistics view.

5.6.2 OVERLAY CHART

The overlay chart shows that the LCOE values ranges from $0.01018 to $0.01500 with a 98% probability while PPA values ranges from $0.11000 to $0.18000 with a 10% probability as shown in figure 14. PPA has the highest price values with low probability because it considers factors like inflation, depreciation and risks for the operational cost while LCOE does not consider all those factors. According to Branker et al. (2011), LCOE only considers the lifetime generated energy and costs to estimate a price per unit of energy generated, different actual financing methods available for different Renewable Energy Technologies (RETs) are not examined.

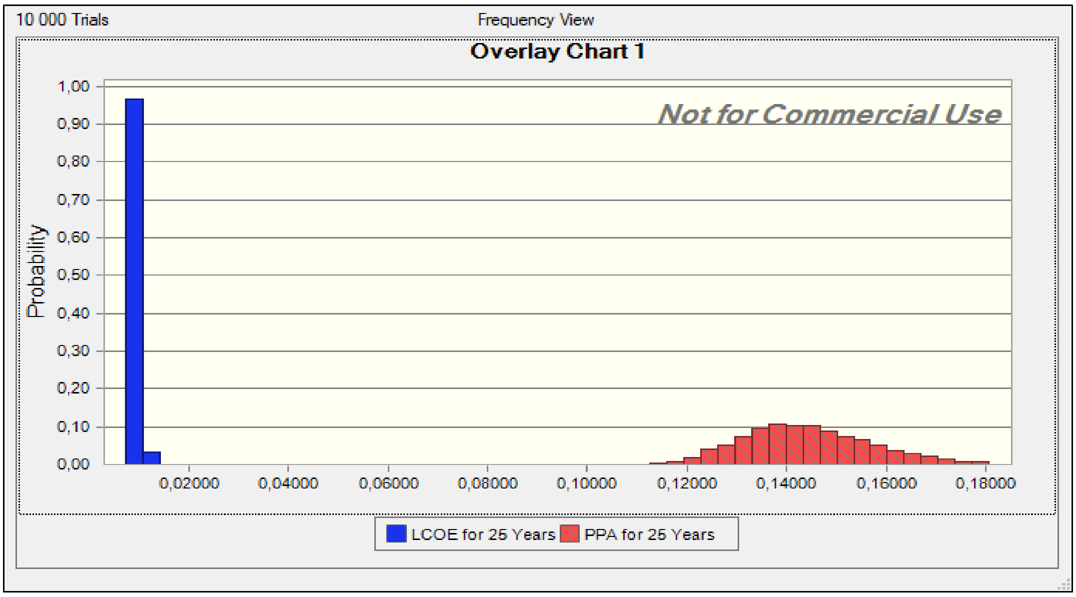


Figure 14: Overlay chart (Author, 2021)

5.6.3 TREND CHART

The trend chart displays the certainty bands for various forecasts on one plot. The trends for LCOE and PPA are as shown in figure 15, their price certainty values ranges from $0.01 to $0.17. It also shows the probability increase in LCOE and PPA values i.e LCOE has the lowest values while PPA has the highest values. Since the spread of the lines are increasing upwards towards the positive slope, it means that the investment is profitable.

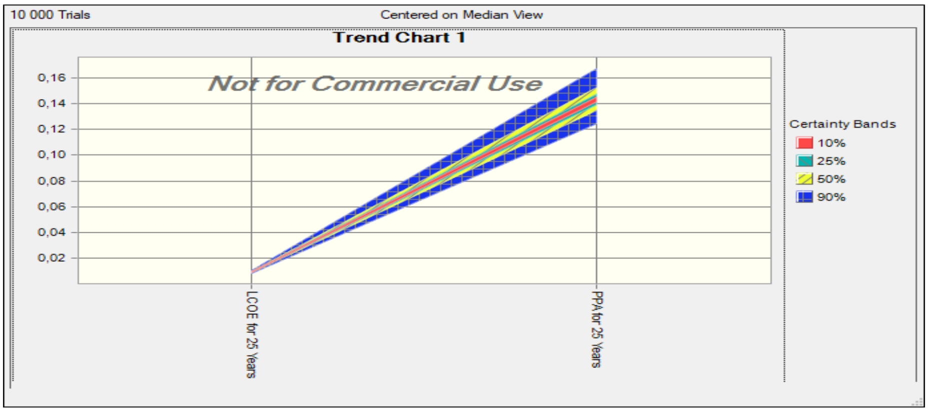


Figure 15: Trend chart for PPA and LCOE (Author, 2021).

5.6.4 SCATTER CHART

The scatter chart shows the relationship between two variables of forecasts and/or assumptions as plotted against each other. Figure 16 shows the correlation factor of 0.297 between LCOE and PPA for 25years in terms of price. It is a positive factor, a value more than 0 that increases towards the positive direction. MCS examines the effects of all possible combinations of variables which assist managers to make better decisions.

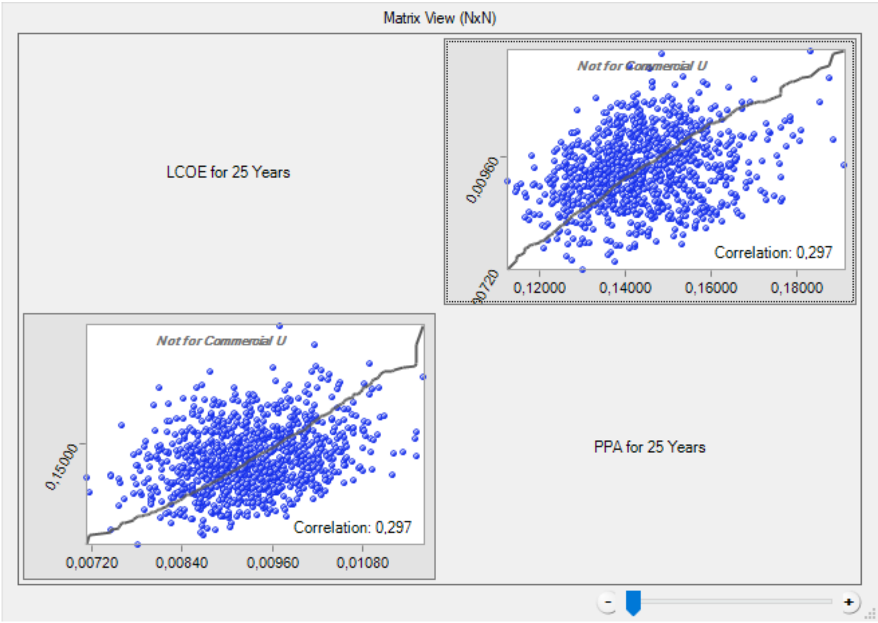


Figure 16: Correlation between LCOE and PPA (Author, 2021).

5.6.5 SENSITIVITY CHARTS

Sensitivity shows the relationship of the variables with the predictions. The annual degradation of LCOE and PPA escalator are 49.6% and 59.9% respectively. Their sensitivity depends on first year of production, this means that if first year production is increased by 100%, LCOE and PPA will decrease by -25.3% and -20.3% while total initial system cost will increase by 14% and 18.5% respectively as shown in figure 17. Several factors affect the variation in output and cost of generated electricity like efficiency, operation, complexity, capacity of generation, lifetime and location of the power plant. Most investors would prefer to invest in a system with lower initial cost, lower degradation rate, lower LCOE yet with higher energy output.

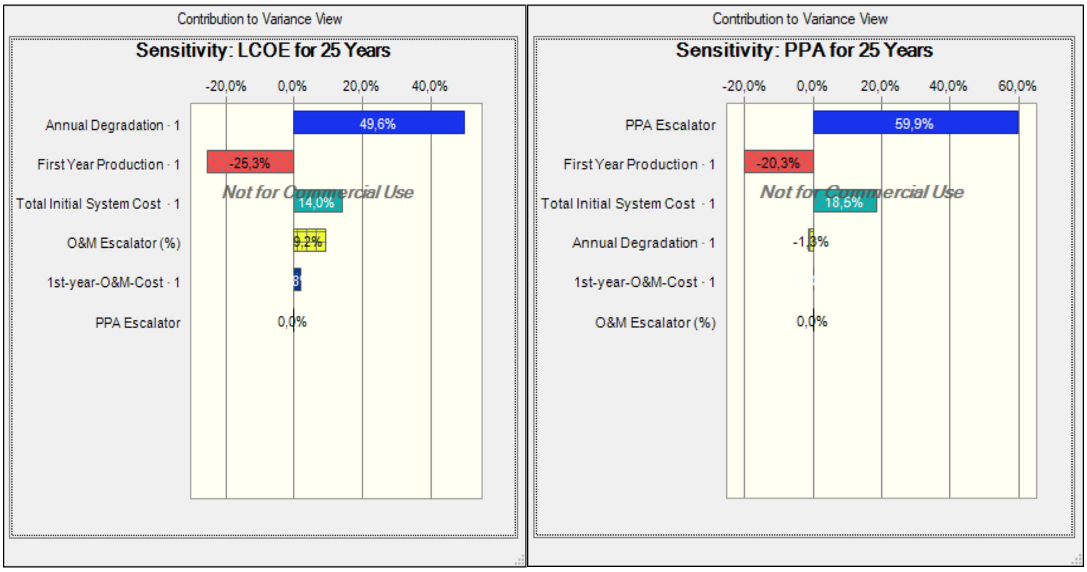


Figure 17: Sensitivity for LCOE and PPA (Author, 2021).

5.7 SUMMARY OF LCOE AND MCS

When it comes to designing of solar system, proper considerations should be made not only on CAPEX, OPEX and total energy production but also on all other factors for choosing solar PV panels and installation site. This is done by using the following criteria; NPV, LCOE and life cycle cost. NPV is the total present value obtained by total cash flows which includes the initial cost of all the systems components, O&M and investment costs plus the discounted present values of all estimated future costs during the life time of the system. LCOE is commonly used in the design and optimisation of energy systems, the process is as summarised in figure 18. It is expressed as the ratio of the total annualised cost of the system to the annual energy delivered by the system. Life cycle cost include all the costs over the systems lifetime from initial investment (system construction) and capital costs, to O&M of the power plant, such as fuel and financing cost. The lower the cost the higher the economic potential of the project.

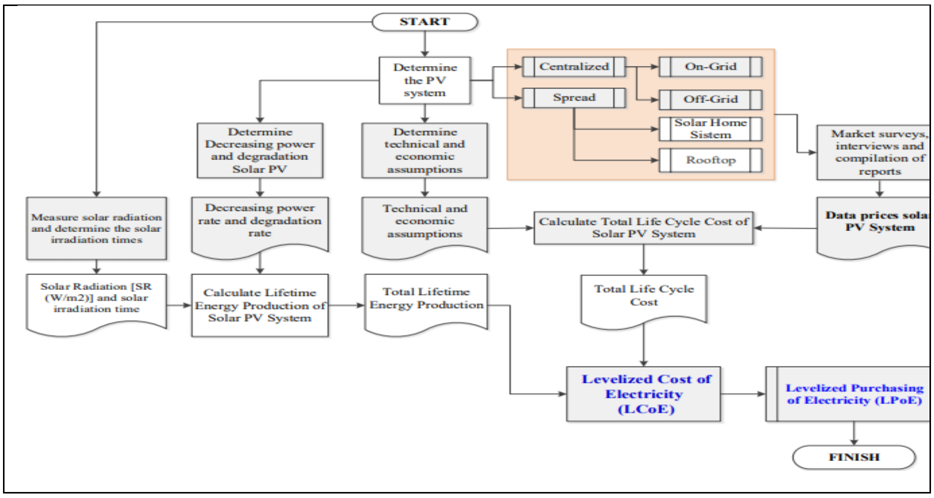


Figure 18: The LCOE research flow chart (Sinaga et al., 2019)

CHAPTER 6

6.0 CONCLUSION AND RECOMMENDATIONS

6.1 FINDINGS

Monkey Bay like many parts of Malawi and Africa as a whole has the potential of harnessing solar energy given the plenty amount of sunlight it receives throughout the year. The main objectives of this study was to assess the viability of solar energy at MMB port and analyse its feasibility for cold ironing. Findings from this research paper shows that 55,754.44kWh/year of electricity can be generated with only 359 solar panels achieving a 90% port's energy savings. Plus, the solar project is profitable or will break even as revealed by the Power Purchase Agreement (PPA) which is higher than the Levelised Cost of Electricity (LCOE).

The new electricity structure in Malawi encourages the participation of private sectors (IPPs) in the electricity production industry. The calculated research findings shows that, if Solar PV is implemented at MMB port a total of 33,219.02$/year will be saved from energy bills as the price of power from the national grid is higher and volatile on the other hand solar energy is cheaper and can be offered at a fixed price for a very long time through a power purchase contract.

It is crucial that investment deals for investing in RET be signed on a long-term basis to give room to the investor to recuperate the capital invested in the project. Solar PV technology has a payback period of 8-12years from the first year of production with an economic lifespan of 25years; so, if for example the land tenure is for 15years, then the investor has only 3years to recuperate initial capital invested which is too short a time to gain their returns. Therefore, signing the contract on a long-term basis (20-30years) will allow the investor to make more profits out of the project and can also invest in other projects with the profits made like developing port infrastructure to ease the adoption of solar PV technology.

RET tend to have high initial costs with low O&M costs making it more expensive for investors to take up the project without financial assistance from the government or lending institutions. Thus, to encourage port authority and shipowners globally especially those in cold regions to adopt the technology, financial mechanism from the public authority or financial industry should be put in place to balance and/or minimise technical, economical, social and environmental risks.

6.2 CONCLUSION

The advancement in technology, economic development and high population growth has increased the need for burning fossil fuels to provide energy needed for better living standards. Conventional power generation especially those used by marine vessels at berth has led to a series of harmful gaseous emissions which causes environmental threat and human health issues such as global warming, climate change, acidic rain, diseases and air pollution. Ports that are located close to human habitation must consider a fundamental factor of city-port relations since toxic air emissions from ports may negatively affects inhabitants near harbor areas. It is essential for such ports to handle their operations in an innovative and efficient manner such that they inflict zero or as little negative externalities as possible on local communities.

The aforesaid issues can be mitigated effectively with solar-generated Onshore Power Supply (OPS). Solar energy is a clean renewable energy resource that is clean/pure, infinite, costless, sustainable with potential to improve energy efficiency, mitigate harmful air emissions from maritime shipping industry. It can be harnessed from everywhere and has minimum emissions during its lifecycle as compared to the over-extracted fossil fuels.

So far, solar Photovoltaic technology has been adopted and implemented by most ports in Asia, Europe and USA. From the SWOT analysis on the implementation of solar photovoltaic technology in leading ports, the researcher identified that these ports have adopted solar technology and they are flourishing though they are located in areas with harsh weather conditions not very conducive for solar energy generation (cold, snowy with weak solar irradiation and short hours of sunlight) as compared to most African countries where the technology has not yet been adopted especially in shipping ports. Implementation of RES in Africa will have a remarkable effect on the reduction of global air emissions and boost port's energy efficiency.

Barriers/challenges to solar technology in Malawi include: No government subsidies in renewable energy investments, this puts most investors at a disadvantage. On the same, the price of selling electricity in the country is too low, this also discourages private investors as it will take more years for them to recuperate the invested capital. The GoM should introduce incentives to encourage private investors to invest in RETs and introduce a better price of sale/purchase of electricity.

Another challenge is lack of local companies and skilled workforce to manufacture and install panels making it more expensive as it has to be imported from Asian countries along will labor to fix the purchased panels. The availability of local specialists would render the whole purchase and installation process of the system affordable.

OPS and solar PV are expensive technologies as compared to fossil fuels when used by berthed ships in the sense that there is need for infrastructure development to enhance the compatibility of ship-to-shore power supplies for instance the purchase of voltage (i.e. step-down transformers) and frequency converters. Costs incurred by Port Authority (PA) during installation, O&M of the technology is transferred to shipping lines through tariff structures/electricity charges ($/kWh) which is most of the times quite high. This may make both PA and shipowners reluctant to invest in and/or adopt the technology. Often times, laws and regulations make it compulsory for ship owners to comply by imposing stiff punishment to polluters. Shipowners can reduce such costs by connecting as minimum load as possible when connected to

OPS in such a way ports energy demand will be sufficient for all ships calling the port

Lastly, maritime ports play an important role in facilitating international and domestic trade of goods and services aiding the rapid economic growth as maritime cargo volume and passenger movement increases. Against this background, shipping is responsible for environmental and human health concerns due to huge amount of air pollutants and GHGs emissions which affect port workers and local communities negatively. The adoption and implementation of solar energy technology for cold ironing at MMB port will not only improve ports' energy efficiency but also mitigate air pollutants and GHGs emissions along with their negative externalities as already examined in this paper through LCOE calculation, sensitivity analysis in MCS and SWOT analysis following the best practices in the benchmarked ports.

In other words, cold ironing using electricity generated form solar photovoltaic technology at Monkey Bay Maritime Base port in Malawi is a viable and feasible option that will mitigate environmental and social issues at the same time brings economical benefits following the reduction in importation of fossil fuels.

6.3 RECOMMENDATIONS

Following thorough study on challenges that Monkey-Bay Maritime Base port, the Malawi energy sector and Africa collectively are currently facing. The researcher came up with the following recommendations:

- ✧ MMB port should adopt and implement solar photovoltaic technology for its OPS considering its numerous benefits in solving environmental and human health issues.
- ✧ The GoM should provide financial incentives that encourage IPPs, port authority and shipowners to invest in OPS and renewable technologies. The funding will help investors to install and develop infrastructures to accommodate shore-side

power supply. Once in place further emission discount fees/subsidy rates to be introduced for implementation by berthed ships. A practical example is learnt from Port of Bergen and ESI as already discussed in this paper.

- The GoM should formulate regulations and policies that enforces protection of the environment especially from pollution emanating from maritime shipping industry. The Malawi energy policy should be updated to include directives that would encourage ports/ships to adopt RET like the directive 2014/94/EU in the European ports. Similarly, as a means of encouraging African ports to adopt the technology, they should not be charged any premiums on cost of electricity sold to ships through OPS in so doing they will see the technology as profitable with less operation cost as compared to the traditional fuels used by auxiliary engines.
- The country's power structure should be more flexible to allow private sectors to participate in electricity generation, transmission and distribution to end-users. If IPPs are allowed to perform other tasks other than production, there will be tough competition between them and ESCOM that will improve the quality-of-service delivery.
- The GoM must also renovate, upgrade or even construct new power generation, transmission and distribution infrastructures as most of them are dilapidated. This will minimise electricity losses, increase access to affordable, reliable and sufficient power system and enhances smooth delivery of port activities and other services in the country.
- Use of shoreside power supply from solar energy should be encourage for all ports around the world especially those that receives strong solar irradiation throughout the year. However, cold regions should make use of the locally available renewable technologies like wind, waves and alternative fuels as collectively would lead to greater reduction in global atmospheric emissions especially from major maritime nations.
- For better strength African ports should pool together share information and resources that would assist them to invest in the vast resources of sunlight the continent is blessed with. As seen from the study Africa is the only continent

which is not a participant to ESI. If Africa can adopt what the European Sea Ports Organisation (ESPO) are currently doing there will be a good relationship between the port and local communities in the port area as emissions will be reduced and the ports will become sustainable, smarter and greener.

If the vast solar potential is unlocked and developed world wide, harmful air emissions will be reduced remarkably, health and well-being will also be improved as well as affordable, reliable and sufficient energy will be accessible globally. Therefore, it is high time we shift from using fossil fuels which are damaging our climate to more environmentally friendly and clean, RES.

The use of shoreside power supply system is the most effective way of reducing air pollution since ships at berth switches off their fossil fuelled engines.The use of solar powered electricity at MMB port will help to increase the reliability of the electricity supply from national grid as it will supply its excess generated power to the main grid which in turn will supply to the local communities. At the same time ESCOM will concentrate supplying its power to other areas other than the port as the port will be generating its own power.

Future research.

More studies should be conducted on the cost-benefit analysis of solar photovoltaic technology on the environment. In other words, how much harmful air emissions will be cut from the shipping industry by generating 55,754.44kWh/year of electricity in this case with Solar PV technology in ports.

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Appendix I

LCOE calculator for Solar PV Project at MMB port in Malawi

OPTONY Solar for Life

Levelized Cost of Energy (LCOE) - Solar PV for Monkey Bay maritime Base port in Malawi

Solar PV Project Cost Calculator

Inputs highlighted in Yellow

System Inputs		Input Description
System Size (kW-DC)	42484,06	*(Please insert the aggregate system size for a site)*
1st-Year Production (kWh)	372 160 366	*(Please insert the aggregate forecasted system production at a site*
Annual Degradation	5,00%	*(Please insert the expected system yearly performance degradation)*
Direct Purchase Inputs		
Cost ($/KW)	$ 883,000	*(Please insert total system cost per Watt. If not available, use the formula: Cost ($/KW) = (Total-system-cost/Total-system-size-in-Kwatts)*
Initial Rebate/Incentive	$	*(Please insert the total value of rebates/incentives received within the first year)*
O&M Cost ($/kW)	9,3000	*(Please insert the per kW O&M cost. If not available, use the formula: O&M Cost ($/kW) = (1st-year-O&M-Cost/Total-system-size-in-kW)*
O&M Escalator (%)	3%	*(Please insert the expected yearly escalation)*
PPA Inputs		
PPA Rate ($/kWh)	0,1019	*(Please insert the per kWh PPA Rate. If not available, use the formula: PPA Rate ($/kWh) = (1st-year-PPA-Cost/1st-year-system-production)*
PPA Escalator	3,00%	*(Please insert the expected yearly escalation. If not uniform, manually insert yearly escalation in Column I)*

LCOE Outputs*		Price per production, the longer the project, the cost will be lower
Direct Purchase		** Compare to expected utility costs over the next 20 years*
20 Year	0,01008	(O&M cost+initial cost)/Production
25 Year	0,00965	(initial cost+ o&m cost)/25 years production
		Benefit for the investor bcs the longer the project, their income will increase
PPA		** Compare to expected utility costs over the next 20 years*
20 Year	0,13018	PPA cost for 20 years/Produce 20 years
25 Year	0,13742	PPA cost for 25 years/Produce 25years

**Undiscounted Analysis*

aug-21

LCOE Calculator

Year	Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)	PPA Escalator (%)	PPA Rate ($/kWh)	PPA Cost ($)
0		$ 37 513 425		-		
2024	372 160 366		$ 395 102	3%	$ 0,1019	$ 37 908 526,7
2025	353 552 347		$ 406 955	3%	$ 0,1049	$ 37 093 493,4
2026	335 874 730		$ 419 163	3%	$ 0,1081	$ 36 295 983,3
4	319 080 993		$ 431 738	3%	$ 0,1113	$ 35 515 619,7
5	303 126 944		$ 444 691	3%	$ 0,1146	$ 34 752 033,8
6	287 970 597		$ 458 031	3%	$ 0,1181	$ 34 004 865,1
7	273 572 067		$ 471 772	3%	$ 0,1216	$ 33 273 760,5
8	259 893 463		$ 485 925	3%	$ 0,1253	$ 32 558 374,7
9	246 898 790		$ 500 503	3%	$ 0,1290	$ 31 858 369,6
10	234 553 851		$ 515 518	3%	$ 0,1329	$ 31 173 414,7
11	222 826 158		$ 530 984	3%	$ 0,1369	$ 30 503 186,2
12	211 684 850		$ 546 913	3%	$ 0,1410	$ 29 847 367,7
13	201 100 608		$ 563 321	3%	$ 0,1452	$ 29 205 649,3
14	191 045 577		$ 580 220	3%	$ 0,1496	$ 28 577 727,9
15	181 493 299		$ 597 627	3%	$ 0,1541	$ 27 963 306,7
16	172 418 634		$ 615 556	3%	$ 0,1587	$ 27 362 095,6
17	163 797 702		$ 634 022	3%	$ 0,1635	$ 26 773 810,6
18	155 607 817		$ 653 043	3%	$ 0,1684	$ 26 198 173,6
19	147 827 426		$ 672 634	3%	$ 0,1734	$ 25 634 912,9
20	140 436 055		$ 692 813	3%	$ 0,1786	$ 25 083 762,3
21	133 414 252		$ 713 598	3%	$ 0,1840	$ 24 544 461,4
22	126 743 539		$ 735 006	3%	$ 0,1895	$ 24 016 755,5
23	120 406 362		$ 757 056	3%	$ 0,1952	$ 23 500 395,2
24	114 386 044		$ 779 768	3%	$ 0,2010	$ 22 995 136,7
25	108 666 742		$ 803 161	3%	$ 0,2071	$ 22 500 741,3
		$ 37 513 425				
20 yrs	$ 4 774 922 273,0797		$ 10 616 532,2525			$ 621 584 434,5198
25 yrs	$ 5 378 539 213,0670		$ 14 405 119,5019			$ 739 141 924,6654