UNIVERSITY OF NAIROBI

FACULTY OF ENGINEERING

DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING

MASTER OF SCIENCE IN ENERGY MANAGEMENT

TECHNO-ECONOMIC STUDY OF A SOLAR PV POWERED COLD STORAGE FACILITY FOR FISH IN SENA AND MRONGO BEACHES IN MFANGANO ISLAND.

BY

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Declaration

I Boniface Okwach, of Reg. No F56/69371/2011 declare that this project is my original work and has not been submitted elsewhere for research. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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Abstract

Fishing is an economic activity predominant in the lakeside region of Kenya. Its sustainability and profitability is however, dependent on value addition alongside demand and supply management. This effort translates to timely sales at good prices without a rush to dispose off in fear of spoilage. To achieve these results, a reliable source of power and refrigeration system with minimal operation and maintenance cost is required. The main objective of this research is to design a cold storage facility for fish operating off solar PV system with thermal storage in Mfangano Island, Homabay County Kenya.

The cold storage facility is motivated by the lack of electricity at study sites Sena and Mrongo beaches which are dependent of purchase of ice from transport trucks which are put in locally fabricated cooler boxes with fish. The ice is replenished every three to four days once melted. These results in high costs and dependence on trucks that if not available can render the fish spoilt if not sold within the shortest time, which would fetch low prices.

The design of cold storage facility was based on daily fish caught and amount of ice required for storage. The quantity of fish was measured using a weighing scale and the mass recorded, the highest production in the year was used in sizing the refrigeration and solar photovoltaic capacity. The refrigeration system was designed based on the thermal load from fish and heat gain from the environment. The solar photovoltaic capacity was thereafter designed to deliver an equivalent electrical energy to the calculated thermal energy with two days of autonomy. The system was finally evaluated for economic feasibility.

The outcomes of the design showed that for Mrongo Beach, 2 refrigeration systems rated 1 kW each and a solar PV of 1.5 kW would be sufficient, on the other hand Sena Beach required 3 refrigeration systems rated 1 kW each and 2.8 kW of solar PV.

Key Words: Solar Photovoltaic, Fish Storage, Refrigeration, Economic Analysis

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List of Abbreviations and Acronyms

A	Area of section [m^2]
ASHRAE	American Society of Heating Air-Conditioning and Refrigeration Engineers
BMU	Beach Management Unit
COP	Coefficient of Performance
C_p	Specific heat of product above freezing [kJ/(kg.K)]
DC	Direct Current
D_t	Decimal portion of time doorway is open
E_{el}	Electrical energy required [kWh]
E_{pv}	Generated photovoltaic energy [kWh]
ESP	Economic Stimulus Programme
FAO	Food and Agricultural Organization
FMC	Farm Milk Cooler
FV	Future Value
GHI	Global Horizontal Irradiance [kWh/m^2]
H	Total global solar irradiation [kWh/m^2]
h_i	Internal surface conductance [$W/m^2.K$]
h_{if}	Enthalpy of infiltration air [kJ/kg]
h_o	External surface conductance [$W/m^2.K$]
HOMER	Hybrid Optimization Model for Multiple Energy Resource
h_{ra}	Enthalpy of refrigerated air [kJ/kg]
i	Applicable rate
I	Irradiance on the module surface [W/m^2]
I_{STC}	Solar irradiance at standard test conditons [W/m^2]
k	Thermal conductivity of wall material [W/m.K]
m	Mass of product [kg]
N	Number of solar panels
NOCT	Nominal Operating Cell Temperature [°C]
NPV	Net Present Value

P_{mod}	PV peak power [W]
P_{off}	Compressor stand-by power [W/m^2.K]
PV	Photovoltaic
q_{il}	Infiltration heat load [W]
q_{il}	Internal load [W]
q_{pl}	Product load [W]
Q_T	Total refrigeration load [W]
q_{tl}	Transmission heat load [W]
SMART	Sustainable Milk for Africa through Refrigeration Technology
SPP	Simple Payback Period
STC	Standard Test Conditions
t	Time
T_{amb}	Ambient temperature [°C]
t_f	Final product temperature [°C]
t_i	Initial product temperature [°C]
T_{mod}	Module operating temperature [°C]
U	Overall coefficient of heat transfer [W/m^2.K]
V	Voltage
WHO	World Health Organisation
x	Wall thickness [m]
γ	Module temperature coefficient on power [%/°C]
Δt	Temperature difference [°C]
η_{mod}	PV module efficiency [%]
η_{ref}	Rated PV module efficiency [%]
ρ_r	Density of refrigerated air, [kg/m^3]
υ	Average air velocity [m/s]

Chapter 1 Introduction

1.1 Background to the Study

Kenya has a plethora of aquatic resources with potential for aquaculture. It covers a stretch of the Indian Ocean shoreline, a portion of Africa's largest freshwater lake (Lake Victoria), and numerous rivers, swamps, and other wetlands, all of which sustain a diverse range of local aquatic species (Ngugi et al., 2007). Fishing is one of the oldest mankind economic activity done for subsistence and for profit (Njagi, 2013). It is no doubt that farmers in suitable places around the country are turning to fish farming as a means of producing high-quality food for their families or for the market, as w

ell as a source of income (Ngugi et al., 2007).

Aquaculture was adopted in Sub-Saharan Africa in the 1950s with the primary goals of improving rural nutrition, generating additional income, diversifying activities to reduce crop failure risk, and creating jobs in rural regions (Njagi, 2013). Aquaculture encompasses a wide range of systems, ranging from small ponds to large-scale, highly intensive commercial operations. Therefore, a transition toward a more business-oriented strategy is required to increase incomes for rural smallholders through aquaculture production (Kioi, 2014).

Kioi (2014) notes that the Kenya Economic Stimulus Program (ESP) was established by the Kenyan government to increase economic growth and bring the Kenyan economy out of a recession caused by a slowdown in the global economy in 2009. Within the program was an initiative to promote fish farming. The initiative, led by the fisheries department, sought to build 200 farming ponds for 140 constituencies in fish farming (Kioi, 2014). One key obstacle to the venture's success is the fish market. Marketing, according to Food and Agricultural Organization, includes all actions related to bringing fish to consumers in the desired form, such as processing, packaging, shipping, storing, and other services (Njagi, 2013).

Photovoltaic cooling has been focused on the creation of equipment for health programs in underdeveloped nations, which has led in the development of commercial refrigeration equipment, mostly for the preservation of vaccines, under the supervision of the World Health Organization (De Blas et al., 2003). According to the socioeconomic framework, these countries have historically been based on the primary sector and have a high level of agricultural productivity, but more than 30% of these resources are still wasted due to a lack of proper food storage (Del Pero et al., 2015). Del Pero *et al.,* further highlights that just about 10% of the population have access to power. Decentralized renewable energy-based power generation options can give viable alternatives in such instances (Laidi et al., 2012).

Renewable energy resources are being used to supply an electrical power source by combining relevant technologies such as photovoltaics, wind turbines, or hybrid technology with a storage system to deliver needed power when these renewable energy resources are unavailable (El-Bahloul et al., 2015). In a year, the distribution of global sun irradiation is rather consistent, with a monthly average value of $150\ kWh/m^2$within tropical-equatorial belt of Africa. As a result, the environment is conducive to the deployment of off-grid solar systems (Del Pero et al., 2015).

To offer perishable goods to consumers at high product quality after harvest, it is advised that the storage environment be controlled at a suitable temperature and humidity level to retain the high quality for a longer period of time (El-Bahloul et al., 2015). A similar observation is made for fish cold storage by Rezki Fajry *et al.,* (2018). Due to the lack of a national electrical grid link in rural areas, a decentralised off-grid system is required to deliver these items to the primary markets. Because of Africa's climate, solar-powered cooling devices have a lot of promise (Kuś et al., 2019).

In a study by Tripathi *et al.,* (2015) they highlight that every year, a substantial share of fruits and vegetables produced in India is wasted due to inadequate transportation infrastructure and a lack of cold storage facilities, resulting in significant losses for farmers as well as a negative impact on GDP. They further note that due to lack of existing infrastructure, farmers' financial strength in participating on an individual basis (resulting from high cost of services), and security concerns, the development of the cold chain in rural areas poses the greatest difficulty.

Seasonal conditions present a substantial difficulty to fishermen. Fish output may be high during the harvest season, while conditions may be the exact opposite during the dry season (Setiawan et al., 2021). The fishing business is one of the most energy-intensive industries in the world, due to rising demand for and supply of fisheries and aquaculture goods. Electricity and liquid fuels are the primary energy sources in the fishing industry. Refrigeration equipment consumes a significant amount of electricity (Setiawan et al., 2021).

1.2 Statement of the Problem

Fish may be made more valuable by performing some simple processing, which increases the market value (Njagi, 2013). Refrigeration is necessary to store perishable products like fish, but it is out of reach for most fish farmers. Njagi (2013) further notes that as a result of perishability, it is recommended that the farmer take fish to the market as soon as possible and sell it, as keeping the fish for too long will get it spoilt making it unsafe to eat. If fresh fish is not utilized right once or stored in the refrigerator, the protein nutrients will degrade (Setiawan et al., 2021).

Increased emphasis on productive use of energy and energy for income production is one of the primary discourses and policy framework approaches to enhance energy access within the Sub-Saharan Africa (Opoku et al., 2016). Solar-powered refrigeration is one of the direct application of productive use of solar energy for income creation that has the potential to significantly improve socio-economic development of individuals in rural communities.

Food preservation is one of the most pressing concerns in rural parts of developing countries, where settlements are often not connected to the electric grid or where electricity is only accessible for a few hours per day (Del Pero et al., 2015). This research is premised on the fact that Suba North constituency lacks a reliable supply of electricity which inhibits fish processing and storage besides sun drying which would essentially promote a higher market value of the produce. This study therefore examines fish production within the disadvantaged areas and develop a solar PV based cold storage facility to mitigate the post-harvest losses in Suba North constituency. The study was done within Mfangano Island; the Island is not connected to the national grid and depends on thermal power generation for its electricity needs.

1.3 Main Objective of the Study

The main objective of this study is to design a cold storage facility for fish operating off solar PV system with thermal storage.

1.3.1 Specific Objectives:

i) Assess the daily fish production and storage demands.

ii) Evaluate weather and solar potential within Mrongo and Sena beaches in Mfangano Island (Suba North constituency).

iii) Design a cold storage and solar PV system.

iv) Perform economic analysis of the cold storage and PV system.

1.4 Rationale and Significance of the Study

Electricity is essential for health care delivery, access to clean water, education, permitting safe and affordable lighting, and economic development, among other things. Because of high infrastructure costs and reliance on fossil fuels, the standard electrification model may not be suited for remote and rural areas in developing countries (Chandra et al., 2020).

In a project dubbed 'No Sex for Fish', promoting women in fish business at Nyamware beach in Lake Victoria cited a need for refrigeration a sole target that was not achieved during its implementation. This would have facilitated preservation and hence delivery of more supplies to Kisumu's larger market (Nathenson et al., 2016). It was observed that bulk supply of fish to Kisumu provides negotiating power in the market. In rural communities, solar PV-powered refrigeration can help microbusinesses with fishing, ice cube sales, and commercial refrigeration among other things. Additionally, small rural store businesses can increase their variety by adding things that can be kept fresh with refrigeration (Opoku et al., 2016).

Remote villages and rural areas with limited access to energy can benefit from small-scale solutions centred on productive processes that can help pave the way to the desired level of development (Ramirez-Del-Barrio et al., 2017). The authors further elaborate that subsequently, there is a chance to promote the long-term growth of such communities by making good use of renewable energy resources in activities that are important to their residents.

The study is important, as it will facilitate cold storage systems designers to develop products that meet needs of fishing communities in remote areas without access to reliable supply of electricity while there exist resources that can provide a sustainable business case in the region.

The research supports the Kenyan government endeavour on poverty reduction through productive use of energy more so in rural areas. Through the fish farming programs and off-grid projects the government has been running, the findings of this study shall inform the value addition component in fish farming by providing a system that will not only be technically feasible but also economically practical.

Chapter 2 Literature Review

2.1 Introduction

This section includes pertinent literature on cold storage of perishable products and the steps considered in designing the same. The literature review contrasts the pros and cons in the choice of system to be designed and elaborates the operational aspects of a cold storage system powered by solar PV.

2.2 Fishing in Lake Victoria, Kenya

The main economic activity in Suba North constituency is fishing. Suba North constituency is a leading fishing zone with over 80 percent of its inhabitants being fishermen. The population also lives on subsistence farming, small-scale businesses and keeping domestic animals (County Government of Homa Bay, 2017).

In a study at Nyamware beach in Lake Victoria, it was observed that boats and workers left at 2:00 a.m. to check the nets for fish. The boats start returning at 11:00 a.m. and continue until the afternoon (Nathenson et al., 2016). At approximately 10:00 a.m., fishmongers arrive at the beach. The timing of arrival of fish falls within a duration when heat starts to increase and therefore fish would go bad much faster if not stored at low temperatures.

Fishermen's social cultural practices have had a significant impact on the availability and use of sanitation facilities, fish handling facilities, and artisanal fish processing techniques in Lake Victoria's fishing settlements. Lack of understanding, lack of facilities, poverty, inadequate community leadership, and a lack of alternatives to fish processing such as sun drying are among the issues (Kioi, 2014).

When a community cannot buy into a social initiative, it is doomed from the start. There will be dispute over problems such as project siting, project security, community part financing the project by offering free/minimized manual labour for stages among others (Babayomi & Okharedia, 2019).

2.3 Refrigeration for Preservation

Refrigeration has recently become a need in human life, yet the high energy consumption of refrigerators has long been a significant challenge to various countries (Opoku et al., 2016). This means that reducing the power consumption of refrigerators (and hence the stress on the national grid) or offering alternate means of powering them has a large potential to reduce the burden on the national grid. Vaccine coolers are an excellent solar application. These coolers are constructed in accordance with WHO guidelines (Secop, 2012). For solar panel selection and sizing, it is critical to determine the compressor's starting current. This means that the panel must be selected and sized based on the cooling demand of the targeted load. Secop (2012) propose that use of ice packs can be used as storage instead of a battery pack. The advantage of ice packs is that they do not require any upkeep. The ice packs might be a built-in feature of the appliance or just plastic bags inserted into the appliance.

The dairy industry in Kenya has benefitted from development of varied solar cooling systems. In Kenya, there are about 850,000 small-scale dairy producers, with roughly 85% of them lacking connection to the national power grid. As a result, for the great majority of smallholder dairy farmers in Kenya and other less developed locations throughout the world, there has not been an affordable option for on-farm milk chilling (Foster et al., 2016).

PV-based solar cooling with heating systems encounter additional roadblocks, such as the high cost of battery storage, which is essential for continuous operation of the system during periods of low solar output (Kuś et al., 2019). Recent develops in photovoltaic refrigerators use thermal storage (ice storage) rather than electrochemical battery storage, and the cooling system and the PV panel are connected directly. It eliminates the requirement for battery storage by keeping ice in the refrigerator walls. As a result, there is no need for costly battery storage or replacement. In another solar cooling solution, the sensible and latent heat of frozen water held in a 450 l tank is used to accumulate energy. This method similarly avoids the use of electrochemical batteries, which have a variety of disadvantages such as high cost, maintenance, short product life cycle, and severe environmental effects (De Blas et al., 2003).

In the past, many initiatives focused on sorption refrigeration, which employ solar thermal collectors as a heat source because it was often less expensive than photovoltaics. PV refrigeration has recently become a highly attractive choice, thanks to a significant fall in the cost of producing PV modules and the development of small-size DC compressors (Del Pero et al., 2015). PV modules, absorption refrigerator, two heat exchangers (evaporator and condenser), battery storage, electrical heating element, and control system are the key components of the cooling system (Kuś et al., 2019).

2.4 Solar PV Refrigeration

Solar refrigeration, however less apparent, has gotten a lot of interest from academics and industry. Solar electric, thermomechanical, and sorption refrigeration technologies are three types of technologies that have been developed to gather solar energy for refrigeration (El-Shaarawi et al., 2013). The capital cost of photovoltaic solar panels, on the other hand, is falling, which adds to more favourable financial metrics (Kuś et al., 2019). One of the main problems of fishermen in a tropical area is preserving sea foods as soon as they are caught (Hossain & Talukdar, 2019). It looks to be a challenge in particular when they are in the deep sea for a few weeks and need to preserve the fish to maintain its quality. Fishermen, in most situations, keep ice with them to do so. However, while this technology is not primitive, it does result in a significant energy loss.

When compared to a traditional 12/24 V DC battery-powered system, the applications suited for solar powering are virtually limitless. Cost, sunshine, and location are the most common limitations (Secop, 2012). PV module current and power outputs are roughly related to sunshine intensity. The parameters of the load determine the output current and operating voltage of a module at a particular intensity. The demand has to be studied before the load parameters are considered.

A PV generator, thermal energy storage, and a control system are also included in the concept framework to assure the refrigerator's reliable operation under various reference situations (Del Pero et al., 2015). The ability to connect a PV generator to a DC load eliminates the need for inverters or converters. Del Pero *et al.,* (2015) research reported feasibility analysis of a freestanding DC solar refrigerator powered by PV energy, appropriate for food preservation in rural areas, with a particular focus on Africa's tropical-equatorial region.

Photovoltaic-based vapour compression refrigerators are typically basic systems made up of photovoltaic generators that generate electrical energy from the sun's radiant energy to power the vapour compression thermodynamic cycle. In addition, energy storage media are frequently necessary to operate the system when solar energy is unavailable or insufficient (El-Shaarawi et al., 2013). A wide range of cooling and air conditioning systems based on renewable or waste energy have been developed in order to satisfy increasingly stringent environmental goals set by the worldwide community, such as reductions in primary energy consumption and greenhouse gas emissions (Kuś et al., 2019).

Solar-powered refrigerator performance tests in a variety of temperature zones significantly indicate solar energy as a viable refrigeration energy source (Setiawan et al., 2021). According to test results, the refrigerator functioned well in a variety of climates and places. Solar-powered refrigeration systems have also been studied to determine the various factors that influence system performance (such as time of day and cooling load). Given the maturity of solar cooling systems and the agriculture sector's issue of keeping food goods in off-grid areas in hot and humid nations, solar cooling systems are seen as particularly desirable (Sadi & Arabkoohsar, 2020).

2.5 Related Research Works

A number of scholarly work has been conducted to assess viability and success of solar powered DC vapour compression refrigeration. A study by El-Bahloul *et al.,* (2015) showed that this technology can be successfully employed for post-harvest agricultural transportation refrigeration in remote hot arid places. In another study Thalib *et al.,* (2021) highlight that following the trend in fish production, cold storage encourages fishermen to retain fish obtained in good condition and sell them at a high and affordable price. Fishermen can stockpile excess fish and sell them when demand is high. This observation resonates with that of Setiawan *et al.,* (2021).

Hossain & Talukdar (2019) developed and evaluated performance of a solar-powered micro cold storage system with battery backup. They determined that it could be a viable solution for reducing wasting and degradation of marine food during storage and shipping in deep sea areas.

The fact that cooling demand and solar energy availability coincide is one of the reasons why solar cooling is becoming more popular (Kuś et al., 2019). Further, the severity of produce spoilage is during summer when production is at its peak (Sadi & Arabkoohsar, 2020). Solar cooling systems also eliminate some of the limitations of traditional grid-powered vapour compression units (Kuś et al., 2019).

Photovoltaics for Sustainable Milk for Africa through Refrigeration Technology (PV-SMART) has created a cheap solar powered Farm Milk Cooler (FMC) to increase the value of milk from remote producers by allowing them to send chilled milk to central collection sites rather than warm milk. FMCs are also used by the farmers to preserve various farm products like eggs, meat, fruits, and vegetables (Foster et al., 2016).

While few related research works have been stated, many more research work have been done and published on storage of fish in remote tropical areas. More research can still be done to achieve even better results for more efficient preservation of fish produce.

2.6 Research Gap

According to several research, sun cooling could be particularly useful in tropical and subtropical locations. Solar-based cooling systems, which take advantage of abundant solar energy, have been identified as a viable technology in various Asian locations, particularly in countries that are physically aligned with the equator. Kenya itself lying along the equator has conducive weather year long to sustain fish preservation through thermal storage.

There is need for assessment of ways to reduce loss of fresh fish and wastage before it is delivered to the final customer. While the customers are available fish production is still low, this gap needed to reduce by improving on ways of storage of fresh fish caught by the fishermen.

Research was also necessary in preserving fish to enable fishermen earn more from their catch without exploitation by middlemen and people who sell ice for preservation of the fish caught.

2.7 Chapter Conclusion

This section reviewed existing research covering solar PV cooling and the key aspects in designing a system that utilises thermal storage in place of the traditional electrochemical battery storage.

It also includes pertinent literature on cold storage of perishable products and the steps considered in designing the same. The literature review contrasts the pros and cons in the choice of system to be designed and elaborates the operational aspects of a cold storage system powered by solar PV.

Chapter 3 Theoretical Framework

3.1 Introduction

This Chapter explains the approach that was taken in determining the cold storage facility in two fronts; the refrigeration system and the solar PV system. The applicable formulas to arrive at the intended system are discussed here.

3.2 Refrigeration System Sizing

To design a solar powered cold storage facility, the refrigeration design is based on ASHRAE handbook (2014, p. 369). The total refrigeration load comprises of; (1) transmission load, heat transferred through the enclosing surfaces; (2) product load, heat emanating from the products in the refrigerated space; and (3) infiltration load, heat gained from air penetrating into the refrigerated space.

The total refrigeration load becomes;

$$Q_T = q_{tl} + q_{pl} + q_{il} \tag{3.1}$$

Transmission load is determined as;

$$q_{tl} = UA\Delta t \tag{3.2}$$

Where, q_{tl} is transmission heat load, A is outside area of section and Δt is the temperature difference between the outside air and the refrigerated space.

The overall coefficient of heat transfer, U, is determined as;

$$U = \frac{1}{1/h_i + x/k + 1/h_o} \tag{3.3}$$

Where, U is the overall heat transfer coefficient, x is the wall thickness, k is thermal conductivity of wall material, h_i is the inside surface conductance, and h_o is the outside surface conductance.

The product load is calculated by;

$$q_{pl} = m * C_p * (t_i - t_f) \tag{3.4}$$

Where, q_{pl} is the average cooling load, m is the mass of product, C_p is specific heat of product above freezing, t_i is initial product temperature and t_f is the final product temperature.

Infiltration heat load by air exchange is determined as;

$$q_{il} = v * A * (h_{if} - h_{ra}) * \rho_r * D_t \qquad (3.5)$$

Where, q_{il} is the infiltration heat load, v is average air velocity, A is the opening area, h_{if} enthalpy of infiltration air, h_{ra} enthalpy of refrigerated air, ρ_r is the density of refrigerated air, D_t is the decimal portion of time doorway is open.

According to ASHRAE (2014, p. 376), a safety factor of 10% is applied to the total refrigeration load to cater for possible discrepancies that would arise between the design and actual operation.

3.3 Solar PV Sizing

The working point of the PV generator is governed by the PV array arrangement, the prevailing irradiance, and the temperature in the system described. The load's power requirement is determined by the number of refrigeration circuits in operation as well as the refrigeration system's thermodynamic state (De Blas et al., 2003). The key energy requirement is the compressor's power demand in a vapour compression refrigeration system. It is critical to calculate the optimal capacity of the solar PV module and storage required to run the refrigerator efficiently when sizing the solar PV system (Opoku et al., 2016).

The energy balance of the system can be established using the correlation (Del Pero et al., 2015);

$$E_{el} = \frac{Q_T}{COP} + (P_{off} * t) \qquad (3.6)$$

Where, E_{el} is the electrical energy required, Q_T is the refrigeration load, COP is the compressor coefficient of performance, P_{off} is the compressor stand-by power and the auxiliaries and t is the time interval.

The solar PV energy production is determined as;

$$E_{PV} = \frac{P_{mod} * H * N}{1000} \qquad (3.7)$$

Where, E_{PV} is the generated PV energy, P_{mod} is PV power output, H is the total global solar irradiation, and N is the number of solar panels.

Module efficiency is established as;

$$\eta_{mod} = \eta_{ref}(1 - (\gamma * (T_{mod} - 25))) \tag{3.8}$$

Where, $\eta_{ref}$is the rated module efficiency, γ is the module temperature coefficient on power, T_{mod} is the module operating temperature.

The module operating temperature can be estimated as;

$$T_{mod} = T_{amb} + \left[\frac{(NOCT - 20)}{0.8} * \frac{I}{1000}\right] \tag{3.9}$$

Where, T_{amb} is the ambient temperature, $NOCT$ is the module nominal operating cell temperature, and I is the irradiance on the module surface.

To achieve at least 48 hours of operation of the system without solar power, the following condition has to be met:

$$E_{PV}{}^{48h} > E_{el}{}^{48h} \tag{3.10}$$

3.4 Economic Analysis

Prior to setting up a solution for cold storage, it has to take unambiguous ownership, which will take care of all the technical aspects that ensure the installation's life span is met. Community support prior to the start of the project is central. Furthermore, as people pay for power services given, the project's long-term success has boosted the project's chances (Babayomi & Okharedia, 2019).

Energy efficiency is crucial for minimizing cold storage operational expenses for fishermen who do not have easy access to electricity (Thalib et al., 2021). Economic analysis in this study is based on two financial indices; simple payback period (SPP) and net present value (NPV). Simple payback period is the duration it takes to recover the capital cost (initial investment) in totality. Simple payback period is given by:

$$SPP = \frac{Initial\ Investment}{Annual\ Savings} \tag{3.11}$$

Net present value is a financial indicator used to determine whether a project will be financially feasible or not. NPV expresses the expected future cash flows worth at present less the initial investment. It is given by:

$$NPV = Initial\ Investment + \frac{FV_1}{(1+i)^{t_1}} + \frac{FV_2}{(1+i)^{t_2}} + \frac{FV_n}{(1+i)^{t_n}} \qquad (3.12)$$

Where, FV_n is the future value, i is the applicable rate, and t_n is time. If this value is positive, the project is profitable and viable.

3.5 Chapter Conclusion

This chapter has expounded on the technical approach undertaken to arrive at the design objectives of the study. This has been achieved through a review of relevant formulas adopted for analysis of collected data to achieve the expected results.

Chapter 4 Materials and Methods

4.1 Introduction

The research methods and materials are discussed in this Chapter. This covers the criteria within which the study was conducted to arrive at its objective through data collection, assumptions, design, and analysis of results.

4.2 Study Site Description: Sena and Mfangano Island

Suba North constituency is located on the shores of Lake Victoria in Homa Bay County. It is a mostly rural area found between latitudes 0° 21' and 0° 32' south and longitudes 34° 04' and 34° 24' east see Figure 4.1. It is about 400 km west of Nairobi, the capital city of Kenya with a total area of 163.28 km^2 (County Government of Homa Bay, 2017). Suba North constituency has two wet seasons usually from March to June and October to November, but the periods vary to some extent each year. The study was done at Mrongo and Sena beaches located in Mfangano Island, Suba North constituency.

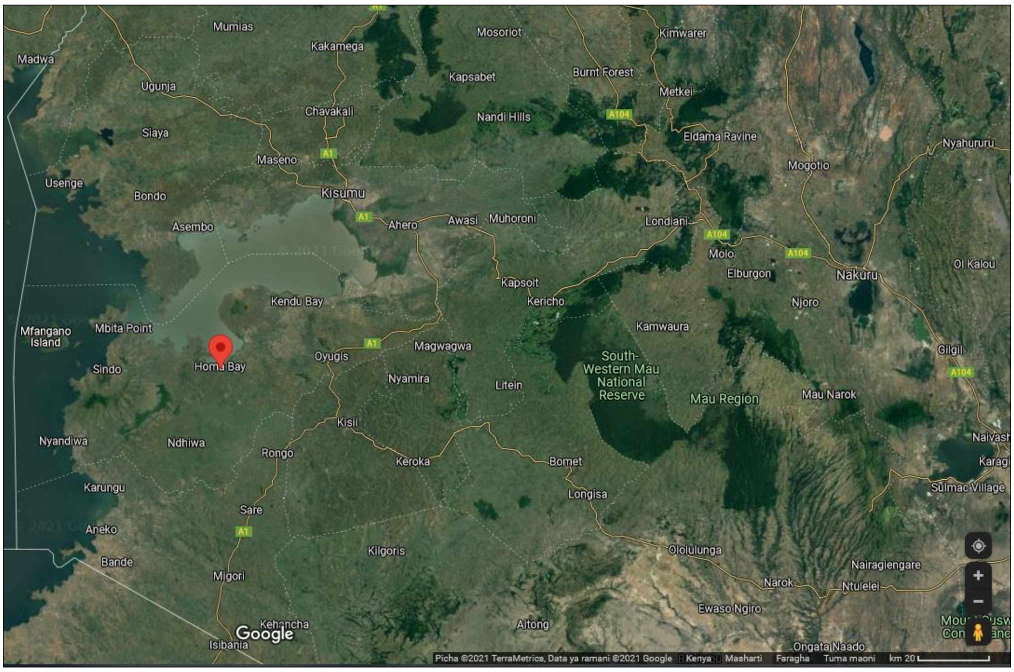

Figure 4.1: Homa Bay County, Kenya. Source: https://cutt.ly/nERYMLe

4.3 Fish Production Data Collection

Fishing data was collected from predominant fishing areas which also lack electrically powered storage facilities. Through interviews with chairmen of beach management units, fishmongers and fishermen, the minimum and maximum daily catch through a year were determined. To simplify the computation of refrigeration load, the fish caught was determined in terms of mass taking an assumption of similar thermal characteristics of the fish breed caught.

4.4 Sizing of Refrigeration System

The fish production data was be used to determine the refrigeration load based on a daily count and storage for up to two days should there be overcast conditions. Equations (3.1) - (3.5) was applied to establish the cold storage facility.

4.5 Sizing of Solar PV System

The solar PV for the refrigeration system was designed based on the level of solar irradiation, ambient temperature, sun hours, and solar module parameters. The amount of energy generation is expected to be greater than the energy required for refrigeration with 2 days of autonomy. Preliminary sizing for the solar system is based on equations (3.6) - (3.10).

4.6 Economic Analysis of Designed System

The inputs for economic analysis include; capital cost, maintenance cost, and other operational costs. The expected output is the duration within which the system will recover its initial investment, and net present value of the project. This would inform on financial sustainability of the designed system and how to best operate it.

A discount factor of appropriate scale must be used when calculating the net present value (NPV) (Verma & Dondapati, 2017), 12 percent is used in this study based on Central Bank of Kenya lending rate. The annual operational costs and maintenance costs are taken as 10 per cent and 1.5 per cent of the capital cost respectively. If NPV is negative, the project is unprofitable and should be reconsidered otherwise if it is positive the project is profit making.

4.7 Chapter Conclusion

This chapter has described the study site and further explained the criteria adopted for collecting data, assumptions made, design and evaluation of results. A systematic design process has been taken from field data to technical design of a cold storage facility and finally economic evaluation.

Chapter 5 Results and Discussion

5.1 Introduction

This Chapter details the data collected from study location and subsequent results upon analysis. The formulas in Chapter 3 are used in calculating the results and recommending the solar powered refrigeration system for the project.

The daily mass of fish caught, ice used and cost of ice and cooler box fabrication was recorded from the study sites in Mfangano Island within Suba North Constituency namely; Mrongo beach managed by Mrongo Beach Management unit (BMU) and Sena beach managed by Sena BMU. Currently ice is bought from fish transport lorries from Nairobi and stored in makeshift cabinets. These are quite expensive and uneconomical since the ice never stays for long hence fish go bad forcing fishermen to sell their catch at throw away prices due to lack of good storage facilities.

5.2 Daily Fish Production and Storage Demands

Fish have different maximum storage life depending on the species. According to ASHRAE (2014, p. 464), fish from the East and West Coasts of the US have a storage life of 10 to 15 days when properly iced and stored in refrigerated rooms at 2°C, depending on their condition when disembarked from the boat. Freshwater fish should only be kept for 7 days if properly iced in containers and housed in refrigerated rooms. Fresh fish should be stored at a temperature of around 2°C with a relative humidity of at least 90% (ASHRAE, 2014, p. 464).

The beaches under study, Mrongo and Sena Beaches (see Figure 5.1) were assessed between 28th July 2021 – 30th July 2021.

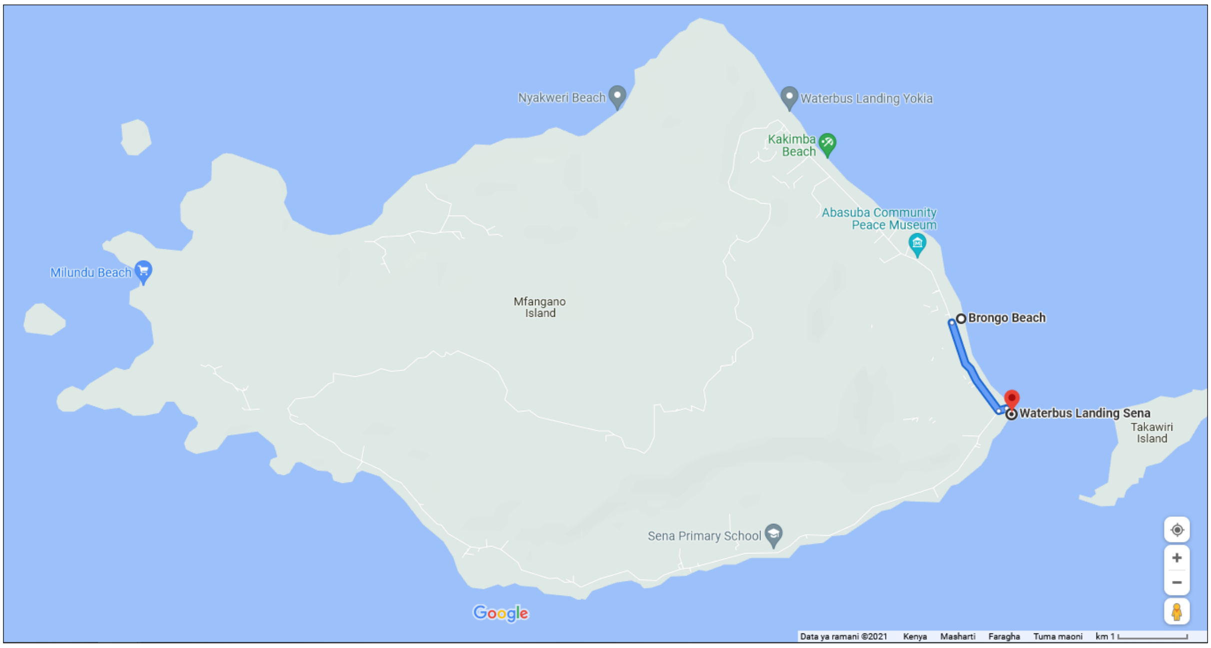

Figure 5.1: Mrongo and Sena beach location, in Mfangano Island. Source: https://cutt.ly/MERmFGD

Mrongo beach is located on coordinates, $0°27'39"S\ 34°03'48"E$ while Sena is located on coordinates, $0°28'23"S\ 34°04'11"E$ in Homabay county.

(a) (b)

Figure 5.2: Study locations in Mfangano Island (a) Weighing scale used in Mrongo BMU and (b) Sena BMU.

The daily quantity of fish caught was determined by using a weighing scale during the time of data collection and records kept at the BMU. The quantities are shown in Table 5.1. The fish caught from the two beaches under study varied over low and high seasons. In Mrongo beach, it was established that the at low season the quantity was four times less than the high season similar to Sena beach. On the other hand, it was observed that Sena beach produced twice the amount of fish to that of Mrongo beach. This indicates that Sena beach is twice as large as Mrongo beach regardless of the similarity in geographical conditions hence demands more ice for cooling requirements.

Table 5.1: Quantity of fish caught daily

		Daily catch quantity (kgs/day)	
#	**Location**	**Low season (Sep-Oct)**	**High season (Mar-May)**
1.	Mrongo Beach	50	200
2.	Sena Beach	100	400

The study sites have fish storage boxes locally made out of wood and aluminium sheets as shown in Figure 5.3. The cooler boxes are opened from the top and ice put at the bottom leaving space for fish above them. The cooler boxes are however, not insulated and therefore increases heat gain from the environment thereby ice melts faster.

(a) (b)

Figure 5.3: Locally fabricated cooler boxes for fish (a) External view and (b) Internal view.

The cooler boxes under study were of two different sizes, large and small as shown in Table 5.2.

Table 5.2: Sizes of cooler boxes

#	Location	Large size (m^3) (quantity)	Small size (m^3) (quantity)	Total quantity of cooler boxes
1.	Mrongo beach	1.3*1.3*1.8 (1)	1*1*0.6 (1)	2
2.	Sena beach	1.9*1*0.8 (3)	1*0.8*0.8 (3)	6

The cooler boxes are loaded with ice of different quantities that lasts 3-4 days before replenishing. The quantities are shown in

Table 5.3.

Table 5.3: Average daily ice used

		Daily ice demand (kgs)	
#	Location	Low season	High season
1.	Mrongo Beach	45	120
2.	Sena Beach	68	120

5.3 Temperature and Solar Potential within Sena and Mrongo Beaches

The two locations are close by (see Figure 5.1) approximately 1.6 km apart and therefore share similar weather conditions. A summary of the clearness index, GHI and air temperature (HOMER, 2021) are shown in

Table 5.4. It is clear that there is substantial solar irradiation across the year. Besides substantial irradiance, clearness index varied between a low of 59.1 per cent in November and a high of 65.1 per cent in February. It is evident that at low irradiance, there is low clearness index and vice versa. Combined high irradiance and clearness index depict that harnessing solar can be achieved successfully with limited intermittence.

The temperature across the year was determined as favourable for solar PV. Ambient temperature in the study sites varied between a low of 20.03 degrees Celsius in July and a high of 21.25 degrees Celsius in March. The annual average temperature was determined as 20.58 degrees Celsius, which is lower than the 25 degrees Celsius standard test temperature for solar PV. These environmental conditions (temperature, irradiance and clearness index) indicate suitability of solar PV applications in the study sites.

Table 5.4: Summary of clearness index, radiation and air temperature at Mrongo and Sena beach

	Mrongo Beach			Sena Beach		
Month	**Clearness Index**	**Daily Radiation**	**Air Temperature**	**Clearness Index**	**Daily Radiation**	**Air Temperature**
Jan	0.635	6.420	20.50	0.635	6.420	20.50
Feb	0.651	6.780	20.97	0.651	6.780	20.97
Mar	0.632	6.640	21.25	0.632	6.640	21.25
Apr	0.609	6.200	20.75	0.609	6.200	20.75
May	0.627	6.030	20.47	0.627	6.030	20.47
Jun	0.633	5.860	20.17	0.633	5.860	20.17
Jul	0.619	5.810	20.03	0.619	5.810	20.03
Aug	0.633	6.260	20.53	0.633	6.260	20.53
Sep	0.632	6.530	20.95	0.632	6.530	20.95
Oct	0.598	6.210	20.72	0.598	6.210	20.72
Nov	0.591	5.990	20.26	0.591	5.990	20.26
Dec	0.630	6.280	20.31	0.630	6.280	20.31
Average	**0.62**	**6.25**	**20.58**	**0.62**	**6.25**	**20.58**

The monthly average solar Global Horizontal Irradiance (GHI) and clearness index at Mrongo beach is shown in Figure 5.4. The annual average GHI is determined as 6.25 $kWh/m^2/day$ and clearness index is 0.62. The clearness index is observed to be high thus ensuring limited scattering and reflection of solar radiation from reaching the earth surface. The irradiance reaching the surface of solar panels is therefore impacted by how clear the sky is and subsequently the output. This is characterised by clearness index.

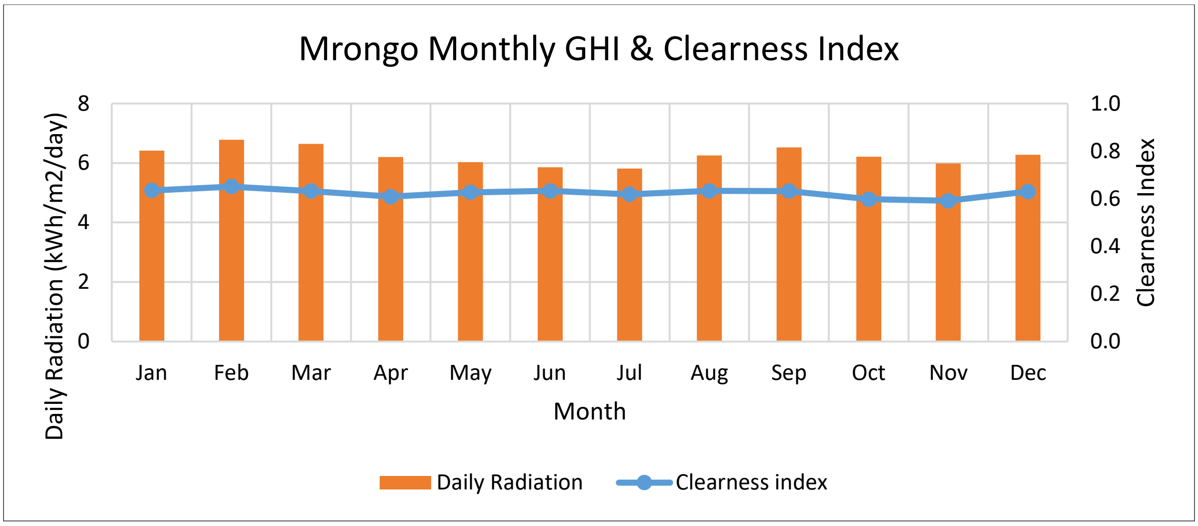

Figure 5.4: Mrongo Monthly Average Solar Global Horizontal Irradiance.

On the other hand, the prevailing monthly average air temperature at Mrongo beach was established as 20.58 degrees Celsius. The temperature profile is shown in Figure 5.5.

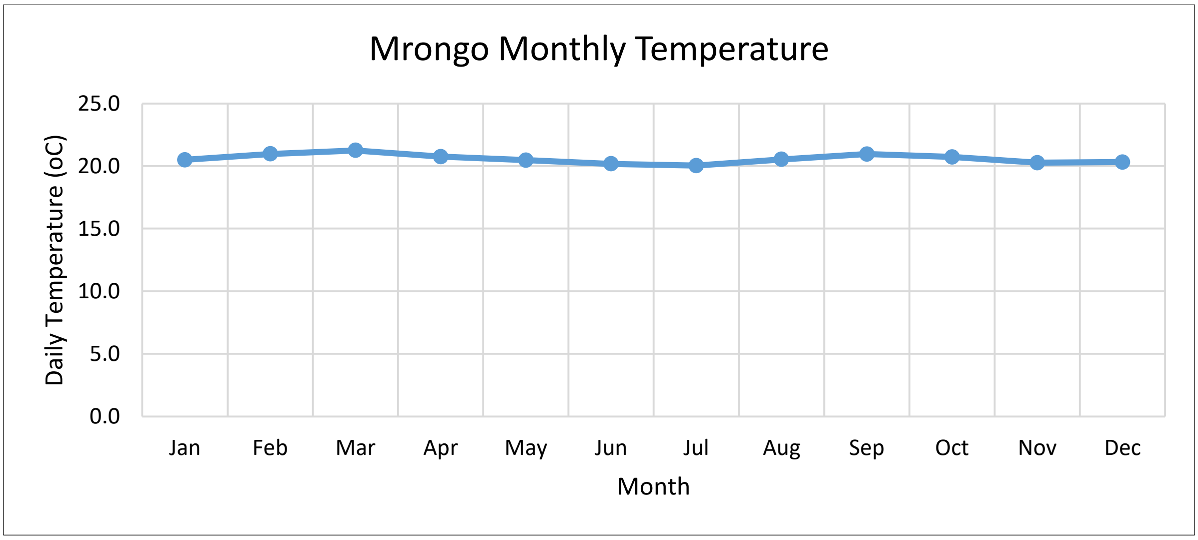

Figure 5.5: Mrongo Monthly Average Temperature.

The monthly average solar Global Horizontal Irradiance (GHI) and clearness index at Sena beach is shown in Figure 5.6. The annual average GHI is determined as 6.25 kWh/m^2/day and clearness index is 0.62.

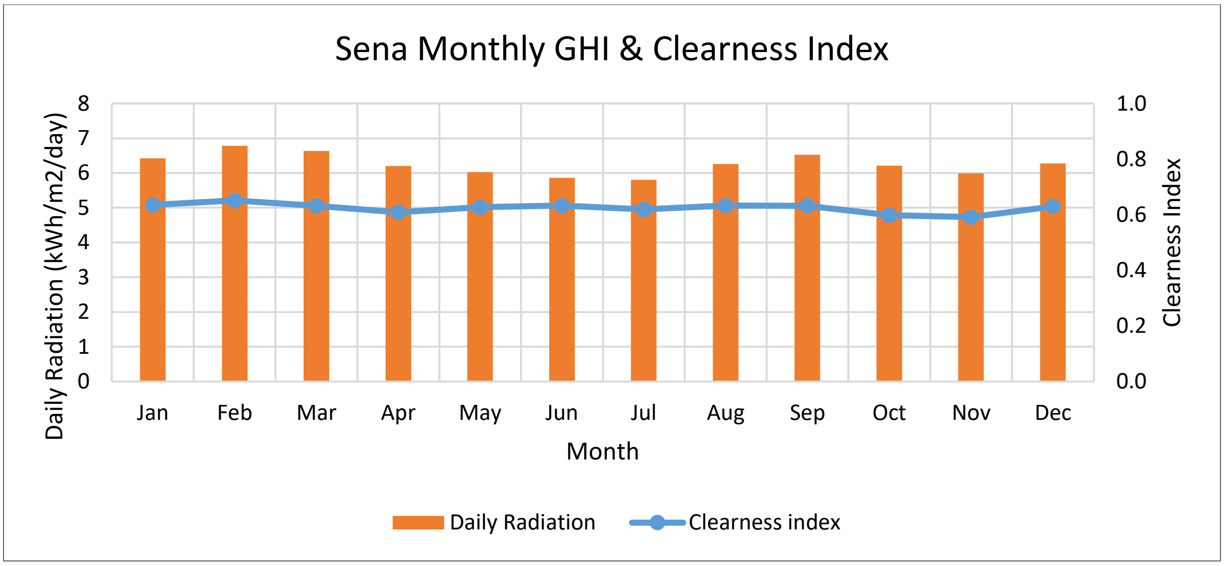

Figure 5.6: Sena Monthly Average Solar Global Horizontal Irradiance.

The prevailing monthly average air temperature at Sena beach was established as 20.58 degrees Celsius. The temperature profile is shown in Figure 5.7.

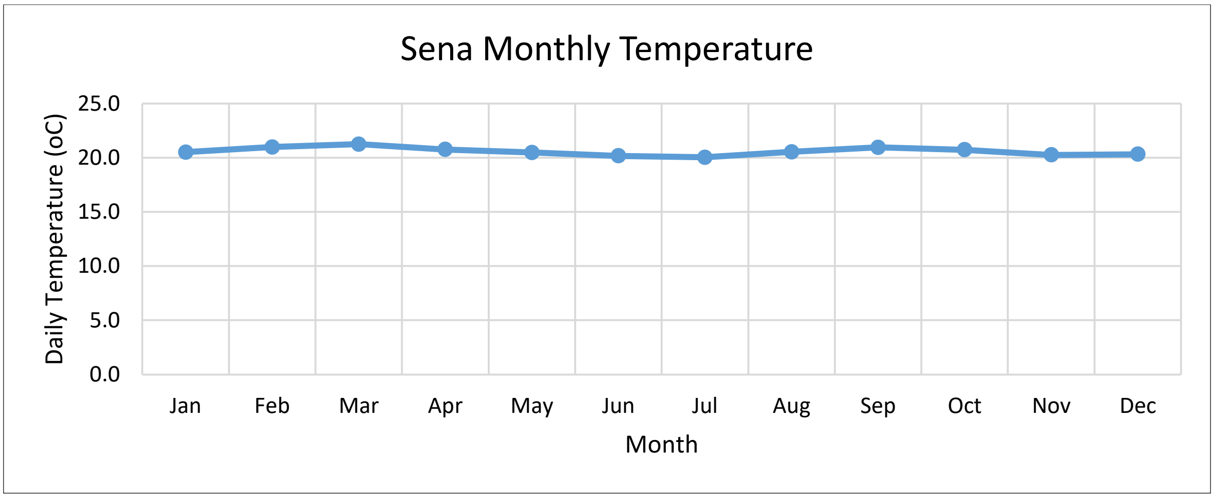

Figure 5.7: Sena Monthly Average Temperature.

5.4 Cold Storage and Solar PV System Design

5.4.1 Cold Storage System Design

The cold storage facility was designed based on the cooling loads contributed by fish and transmission (heat gain) from the environment. An increase in cold storage temperature due to the influence of changes in external temperature and evaporation temperature is the reason of the increase in refrigeration load (Thalib et al., 2021). The predominant fish in the study sites is Nile Perch whose quantity is determined in kilograms. The design for a cold storage facility was based on the high season of fish production which is explained by the need to match peak load without stressing the system nor underperforming.

Cooling on site was achieved using locally fabricated cooler boxes with the cooling medium as ice. The cooler boxes were made out of plain aluminium sheets without insulation while the designed system in this study takes into consideration addition of an insulator sandwiched between two aluminium sheets to improve efficiency.

To determine the cold storage system for implementation, the refrigeration load has to be calculated. From the study sites, the refrigeration load is contributed mainly by the product (fish) and transmission (heat gain through the cooler box surfaces). Infiltration by opening the cooler is ignored as the cooler is opened from the top and since cold air is denser than hot air minimal heat will therefore be gained from infiltration.

Refrigeration load is determined by equation (3.1) which in this case will be a summation of product load and transmission load. The transmission load is established for each cooler box size and summed up. The insulator used in design is 50 mm polyurethane board having considered availability. The properties assumed are summarised as shown in Table 5.5 based on ASHRAE (2014, p. 369).

Table 5.5: Properties of proposed insulation material

#	Parameter	Units	Value
1.	Internal surface conductance	W/(m^2.K)	1.6
2.	Insulation thickness	m	0.005
3.	Insulation thermal conductivity	W/(m.K)	0.0025
4.	External surface conductance	W/(m^2.K)	6

Applying equation (3.3) and properties of insulation in Table 5.5, the overall coefficient of heat transfer, U, is determined as 0.3582 W/(m^2.K).

$$U = \frac{1}{1/_{1.6} + 0.005/_{0.0025} + 1/_{6}} = 0.3582\ W/(m^2K)$$

Considering an average daytime ambient temperature of 27 °C, the subsequent transmission load is determined using equation (3.2) as summarised on Table 5.6.

$$q_{tl\ Mrongo\ large\ cooler\ box} = 0.3582 * (300 - 273) * ([1.8 * 1.8 * 2] + [1.3 * 1.8 * 3])$$

$$= 130.57\ W$$

$$= 11{,}281\ kJ$$

Table 5.6: Thermal load as a result of heat gain from the environment

#	Location	Large cooler box load	Small cooler box load	Transmission load (kJ)
1.	Mrongo Beach	11,281	2,841	14,122
2.	Sena Beach	5,465	3,075	25,620

The product load is determined using equation (3.4), the mass of fish is based on peak season catch which ensures that the designed system has capability to handle the highest load. The parameters used in calculation are based on (ASHRAE, 2014, p. 291) are shown in Table 5.7;

Table 5.7: Thermal load properties for product load calculation

#	Parameter	Units	Value
1.	Initial fish temperature	°C	21
2.	Final fish temperature	°C	0
3.	Perch specific heat above freezing	kJ(kg.K)	3.71
4.	Ice latent heat of fusion	kJ/kg	334
5.	Perch initial Freezing Point	°C	-2.2

The product load was determined as shown in Table 5.8. From equation (3.4) product load becomes;

$$q_{pl,Mrongo} = 200 * 3.71 * (294 - 273)$$

$$= 15{,}582\ kJ$$

Table 5.8: Summary of product load from Mrongo and Sena beach

#	Location	Product load (kJ)
1.	Mrongo Beach	15,582
2.	Sena Beach	31,164

The total loads for the two locations are summarised as shown in

Table 5.9. A safety factor of 10 per cent is added as recommended by ASHRAE (2014, p. 376) to account for any discrepancies between design and actual operation.

Table 5.9: Overall thermal load

#	Load Summary	Mrongo Beach	Sena Beach
1.	Transmission load (kJ)	14,122	25,620
2.	Product load (kJ)	15,582	31,164
3.	Subtotal (kJ)	29,704.14	56,784.41
4.	Safety factor (10 %)	2,970.41	5,678.44
	Total load (kJ)	**32,674.56**	**62,462.85**

The product load was determined to be almost equal the transmission load. In Mrongo beach, the transmission load was 91 per cent of the product load while in Sena beach, it was 82 per cent of the product load. The significant difference in the ratio of cooling loads between the two sites is explained by the difference in the quantity of fish which was two times that of Mrongo. It can therefore be summarised that transmission load significance reduces with increase in product load.

The resulting ice demand for the refrigeration loads compares with the actual loads as shown in Table 5.10. The theoretical determination of ice demand is within range of the actual ice demand, it is noteworthy that the theoretical values have however taken into account insulation. From the load summary, it is evident that the larger load is from fish and not environmental heat gain.

$$Theoretical\ ice\ demand_{Mrongo} = \frac{total\ refrigeration\ load}{latent\ heat\ of\ fusion\ of\ ice} = \frac{32{,}674.56}{334}$$

$$= 97.83\ kgs$$

Table 5.10: Comparison of theoretical and actual ice demand

			Actual Ice Demand (kgs) – collected from field	
#	**Location**	**Theoretical Ice Demand (kgs)**	**Low season**	**High season**
1.	Mrongo Beach	97.83	45	120
2.	Sena Beach	187.01	68	120

In the design for a cold storage facility, a 10 per cent safety factor was taken into consideration as recommended in ASHRAE (2014) to account for any discrepancies between design and actual operation. The theoretical ice demand was compared with the actual and it was determined that for Mrongo beach, 97.83 kgs would be required in design while the actual was 120 kgs. This difference can be explained partly by the incorporation of insulation in the design which does not exist for the existing system implying that efficiency would be increased for the cooler boxes saving ice.

In Sena beach, the design value is determined as 187 kgs while the actual is 120 kgs. While it was expected that the value would be lower it turns out high. There are three observations that could have brought about this. First, it could be as a result of accuracy of the fish or ice demand recorded by the users secondly, there is a possibility of oversizing due to additional safety factor last but not least, the assumption in exposure of all the cooler boxes to the direct sunshine however some cooler boxes were sheltered which subsequently reduces the heat gain.

To design a solar powered cold storage facility, days of autonomy have to be taken into account. In this design, two days of autonomy are taken into account, meaning if there is inadequate sunshine for up to two days, cooling will still take place. The load therefore becomes Table 5.11;

$$Total\ load\ with\ autonomy_{Mrongo} = initial\ load * days\ of\ autonomy = 32{,}674.56 * 2$$

$$= 65{,}349.12\ kJ$$

Table 5.11: Design thermal load

#	Load	Mrongo Beach	Sena Beach
1.	Initial total load (kJ)	32,674.56	62,462.85
	Total load with days of autonomy (kJ)	**65,349.12**	**124,925.70**

The cold storage facility is designed based on total load with days of autonomy. This means it can continue operating optimally in the absence of sunshine for two days before performance begin to deteriorate. The resulting thermal load inclusive of days of autonomy is used in sizing the solar PV system in the subsequent section 5.4.2.

5.4.2 Solar PV System Design

The cooling capability would be derived from a refrigeration system powered by solar PV without energy storage. The cooling load with days of autonomy was used to size for the compressor and its prime mover (motor). Coefficient of performance of the compressor is used to derive the required electrical energy to be generated.

When computing refrigeration load, the most conservative approach is to calculate each part at its expected peak value. The combined result can overstate the actual total load by as much as

20 to 50%. Based on analysis of the load data and an understanding of how, or more importantly, when or how often each load element will occur, the designer will often apply a factor ranging from 0.7 to 0.85 to the calculated final total load. That result is the load on which the selection of equipment is premised on.

The electrical energy demand is based on the performance of the refrigeration system and the thermal load. The compressor (Bitzer) and DC motor (Creusen) selected for this design is based on research by De Blas *et al,* (2003). The authors determined the average coefficient of performance of the compressor as 2.4. The electrical energy is calculated using equation (3.6) and power demand calculated based on 5 peak sun hours is summarised on Table 5.12.

$$E_{el,Mrongo} = \frac{Q_T}{COP} + \left(P_{off} * t\right) = \frac{65{,}349.12}{2.4} + 0$$

$$= 27{,}228.8\ kJ$$

$$P_{peak,Mrongo} = \frac{design\ electrical\ energy}{time} = \frac{27{,}228.8}{3{,}600 * 5}$$

$$= 1.513\ kW$$

Table 5.12: Design electrical load

#	Load	Mrongo Beach	Sena Beach
1.	Design thermal energy (kJ)	65,349.12	124,925.70
2.	Design electrical energy (kJ)	27,228.8	52,052.38
3.	Design peak power demand (kW)	1.5127	2.8918

A Jinko 350 W_p solar panel is selected for the design with details summarised on. The performance of selected solar PV panel Jinko 350 W was determined based on the name plate information. While the rated efficiency of the module was 19.06 per cent, the actual efficiency if implemented under the study site conditions would be 16.84 per cent largely impacted by temperature.

Table 5.13: Proposed solar PV properties

#	Parameter	Units	Value
1.	Model		JKM350M-66HB
2.	Maximum Power (Pmax)	W	350
3.	Maximum Power Voltage (Vmp)	V	36.69
4.	Maximum Power Current (Imp)	A	9.54
5.	Open-circuit Voltage (Voc)	V	43.65
6.	Short-circuit Current (Isc)	A	10.25
7.	Module Efficiency STC	%	19.06
8.	Temperature coefficient of Pmax	%/°C	-0.35
9.	Nominal operating cell temperature	°C	45
10.	Dimensions	mm	1,840*998*35

The design of solar system commences with determination of its operating conditions. The cell operating temperature is determined using equation (3.9) as 58.25 °C.

$$T_{mod} = T_{amb} + \left[\frac{(NOCT - 20)}{0.8} * \frac{I}{1000}\right] = 27 + \left[\frac{(45 - 20)}{800} * 1000\right]$$

$$= 58.25\,°C$$

Subsequently the module efficiency is determined using equation (3.8) as 16.84 per cent and power output as 309 W.

$$\eta_{mod} = \eta_{ref}(1 - (\gamma * (T_{mod} - 25))) = 19.06 * (1 - \left(0.35\% * (58.25 - 25)\right))$$

$$= 16.84\%$$

$$P_{output} = panel\ area * irradiation * \eta_{mod} = (1.84 * 0.998) * 1000 * 16.84\%$$

$$= 309\,W$$

The DC motor details are summarised in Table 5.14

Table 5.14: Proposed DC motor properties

#	Parameter	Units	Value
1.	Model		90L-4GP
2.	Rated Voltage	V	24
3.	Rated current	A	44
4.	Minimum operating voltage	V	22
5.	Maximum operating voltage	V	33
6.	Nominal output power	W	1,100
7.	Speed	rpm	1,500

The compressor (see Figure 5.8) details are summarised in Table 5.15;

Table 5.15: Proposed compressor properties

#	Parameter	Units	Value
1.	Compressor type		II Y
2.	Motor required	W	750
3.	Condenser temperature	°C	50
4.	Cooling capacity	W	1,290
5.	Evaporator temperature	°C	0
6.	Motor speed	rpm	1,450

Figure 5.8: Proposed Bitzer compressor type II Y.

The sizing of the motor matches the compressor and therefore the solar sizing should meet the motor power demand. The number of motors and compressors based on the electrical demand versus the target solar demand is summarised on Table 5.16. The design number of motor/compressor required is rounded up to fully deliver the cooling load.

$$Design\ motor/compressor_{Mrongo} = \frac{target\ solar\ capacity}{motor\ power} = \frac{1.513}{1.06} = 1.43 \text{ motor/compressor}$$

Table 5.16: Summary of PV-Motor-Compressor design

#	Parameter	Mrongo Beach	Sena Beach
1.	Target solar PV capacity (kW)	1.513	2.892
2.	Motor power (kW)	1.06	1.06
3.	Number of motor/compressor required	1.43	2.74
4.	Design motor/compressor required	2	3

The resulting solar PV required is determined as the product of motor power and number of motors divided by the solar PV power output. The final solar PV system is summarised on Table 5.17.

$$Required\ PV_{Mrongo} = \frac{motor\ power * number\ of\ motors}{actual\ solar\ PV\ power\ output} = \frac{1.06 * 2}{0.309}$$

$$= 6.86$$

Table 5.17: Solar PV design requirement

#	Parameter	Mrongo Beach	Sena Beach
1.	Required number of solar PV	6.86	10.29
2.	Final design number of solar PV	6	10

To avoid an over design, the final number of solar PV is estimated as 6 panels rated 350 W for Mrongo beach and 10 panels rated 350 W. It is evident that the figures have been rounded down; this is because the number of motors/compressors required had already been rounded up meaning a safety margin was already catered for. Using equation (3.7), the electrical energy is determined and the design condition as per equation (3.10) is applied to establish the viability of the design. This is summarised on Table 5.18;

$$E_{PV,Mrongo} = \frac{P_{mod} * H * N}{1{,}000} = \frac{309 * 6.25 * 6}{1{,}000}$$

$$= 11.58\ kWh$$

Table 5.18: Electrical design requirement

#	Design condition	Mrongo Beach	Sena Beach
1.	${E_{PV}}^{48h} > {E_{el}}^{48h}$	11.6 > 7.56	19.33 > 14.46

5.5 Economic Analysis of the Cold Storage and PV System

The economic analysis is evaluated based on equations (3.11) and (3.12). To determine the project feasibility the items required and costs were established as shown in Table 5.19 for Mrongo BMU. The design takes into consideration two cooler boxes one large and a small one.

Table 5.19: Estimated Mrongo beach cooler system cost breakdown as at Oct 2021

#	Item	Unit Price (USD)	Quantity	Total Price (USD)
1.	Small cooler insulation	60.00	1	60.00
2.	Large cooler insulation	80.00	1	80.00
3.	Small cooler aluminium sheet	45.00	1	45.00
4.	Large cooler aluminium sheet	75.00	1	75.00
5.	Refrigeration compressors	2,100.00	2.00	4,200.00
6.	DC Motors	500.00	2.00	1,000.00
7.	Heat exchangers	200.00	2.00	400.00
8.	PV panels	157.50	6.00	945.00
9.	Electric cables	100.00	1	100.00
10.	Small cooler fabrication labour	50.00	1	50.00
11.	Large cooler fabrication labour	90.00	1	90.00
12.	Solar PV installation labour	150.00	1	150.00
13.	Solar PV mounting rack	150.00	1	150.00
	Total			**7,345.00**

The resulting savings from ice equates to the cost incurred in ice purchases, which shall be eliminated. The costs are shown in Table 5.20.

Table 5.20: Mrongo beach ice usage cost breakdown

#	Cost	Unit Price (USD/90kg)	Quantity Used (kgs)	Total Price (USD)
1.	Daily ice cost	10.00	0.92	9.17
2.	Annual ice cost	10.00	334.58	3,345.83

Applying equation (3.11), the simple payback period becomes approximately 2 years 3 months as shown in Table 5.21.

$$SPP_{Mrongo} = \frac{Initial\ Investment}{Annual\ Savings} = \frac{734,500}{3,345.83}$$

$$= 2.2\ years$$

Table 5.21: Mrongo beach cooler system simple payback summary

Cost of system	USD 7,345.00
Annual cost of ice	USD 3,345.83
Simple payback period	2.2 Years

To determine the net present value, the cash flow has to be determined, which takes into account cash flow in and out. The annual operational costs and maintenance costs is estimated to be 10 per cent and 1.5 per cent of the system capital cost respectively. The computation is summarised on Table 5.22

Table 5.22: Mrongo beach cooler system cash flow

Gross cash in	USD 3,345.83
Operational costs	USD 734.50
Maintenance cost	USD 110.18
Net cash flow	USD 2,501.16

Using equation (3.12) for a duration of 10 years which is the meaningful life of a refrigeration system, NPV is determined as summarised in Table 5.23

$$NPV = Initial\ Investment + \frac{FV_1}{(1+i)^{t_1}} + \frac{FV_2}{(1+i)^{t_2}} + \frac{FV_n}{(1+i)^{t_n}}$$

$$NPV = -7{,}345.00 + \frac{2{,}501.16}{(1+12\%)^1} + \frac{2{,}501.16}{(1+12\%)^2} + \frac{2{,}501.16}{(1+12\%)^3} + \frac{2{,}501.16}{(1+12\%)^4} + \frac{2{,}501.16}{(1+12\%)^5} + \frac{2{,}501.16}{(1+12\%)^6} + \frac{2{,}501.16}{(1+12\%)^7} + \frac{2{,}501.16}{(1+12\%)^8} + \frac{2{,}501.16}{(1+12\%)^9} + \frac{22{,}501.16}{(1+12\%)^{10}}$$

$$= USD\ 6{,}787.10$$

Table 5.23: Mrongo beach cooler system NPV

Year	Cash Flow (USD)
0	- 7,345.00
1	2,501.16
2	2,501.16
3	2,501.16
4	2,501.16
5	2,501.16
6	2,501.16
7	2,501.16
8	2,501.16
9	2,501.16
10	2,501.16
NPV	**6,787.10**

The project requirements for Sena BMU cooler system are shown in Table 5.24. The design takes into consideration three large cooler boxes.

Table 5.24: Estimated Sena beach cooler system cost breakdown as at Oct 2021

#	Item	Unit Price (USD)	Quantity	Total Price (USD)
1.	Insulation	80.00	3	240.00
2.	Aluminium sheet	75.00	3	225.00
3.	Refrigeration compressors	2,100.00	3.00	6,300.00
4.	DC Motors	500.00	3.00	1,500.00
5.	Heat exchangers	200.00	3.00	600.00
6.	PV panels	157.50	10.00	1,575.00
7.	Electric cables	100.00	1	100.00
8.	Cooler fabrication labour	90.00	3	270.00
9.	Solar PV installation labour	150.00	1	150.00
10.	Solar PV mounting rack	150.00	1	150.00
	Total			**11,110.00**

The ice costs at Sena BMU are shown in Table 5.25.

Table 5.25: Sena beach ice usage cost breakdown

#	Cost	Unit Price (USD/90kg)	Quantity Used (kgs)	Total Price (USD)
1.	Daily ice cost	10.00	1.04	10.42
2.	Annual ice cost	10.00	380.21	3,802.08

Applying equation (3.11), the simple payback period becomes approximately 2 years 11 months as shown in Table 5.26.

$$SPP_{Mrongo} = \frac{Initial\ Investment}{Annual\ Savings} = \frac{11{,}110.00}{3{,}802.08}$$

$$= 2.92\ years$$

Table 5.26: Sena beach cooler system simple payback summary

Cost of system	USD 11,110.00
Annual cost of ice	USD 3,802.08
Simple payback period	2.92 Years

The annual operational costs and maintenance costs is estimated to be 10 per cent and 1.5 per cent of the system capital cost respectively. To determine the net present value, the cash flow has been determined shown in Table 5.27.

Table 5.27: Sena beach cooler system cash flow

Gross cash in	USD 3,802.08
Operational costs	USD 1,111.00
Maintenance cost	USD 166.65
Net cash flow	USD 2,524.43

Using equation (3.12) for a duration of 10 years which is the meaningful life of a refrigeration system, NPV is determined as summarised in Table 5.28.

$$NPV = Initial\ Investment + \frac{FV_1}{(1+i)^{t_1}} + \frac{FV_2}{(1+i)^{t_2}} + \frac{FV_n}{(1+i)^{t_n}}$$

$$NPV = -11{,}110.00 + \frac{2{,}524.33}{(1+12\%)^1} + \frac{2{,}524.33}{(1+12\%)^2} + \frac{2{,}524.33}{(1+12\%)^3} + \frac{2{,}524.33}{(1+12\%)^4} + \frac{2{,}524.33}{(1+12\%)^5} + \frac{2{,}524.33}{(1+12\%)^6} + \frac{2{,}524.33}{(1+12\%)^7} + \frac{2{,}524.33}{(1+12\%)^8} + \frac{2{,}524.33}{(1+12\%)^9} + \frac{2{,}524.33}{(1+12\%)^{10}}$$

$$= USD\ 3{,}153.61$$

Table 5.28: Sena beach cooler system NPV

Year	Cash Flow (USD)
0	- 11,110.00
1	2,524.43
2	2,524.43
3	2,524.43
4	2,524.43
5	2,524.43
6	2,524.43
7	2,524.43
8	2,524.43
9	2,524.43
10	2,524.43
NPV	**3,153.61**

5.6 Research Validation

From literature review, there were no exact matches of studies on design of cold storage facilities with thermal storage for fish. Similar research on cold storage systems with battery, hybrid and varying capacities were established. Aspects like COP, NPV, SPP can however be compared in independently.

In a study by Thalib *et al.,* (2021) they determined that NPV for on-grid PV systems were greater than the utility grid indicating profitability over their entire life of project.

This study was based on a refrigeration system similar to that by De Blas *et al.,* (2003) in their experiment the COP varied between 1.82 and 3.1, an average of 2.4 is used. This value is higher compared with that of an absorption chiller studied by Sadi and Arabkoohsar (2020) which varied between 0.6 and 0.72. Furthermore, their system economic assessment showed that the payback period ranged between 11 years for Evacuated Tube Collectors and 12 years for Flat Plate Collectors while in this study it was 2 – 3yrs. These differences can be explained by the choice of technology in the refrigeration unit.

5.7 Chapter Conclusion

This chapter detailed the outcome of data collected and technical analysis upon which results (system design) are determined. The design process was based on the theoretical framework within which an appropriate sizing of the solar PV and refrigeration units for each site was determined and recommended.

The design and economic feasibility of the cold storage facility is summarised as shown in Table 5.29 below.

Table 5.29: Summary of cold storage facility design

#	Location	Thermal load (kJ)	Refrigeration Units	Solar PV (kW)	NPV (USD)	SPP (yrs)
1.	Mrongo	65,349.12	2*1 kW	2.1	6,787.10	2.2
2.	Sena	124,925.70	3*1 kW	3.0	3,153.61	2.92

Chapter 6 Conclusion and Recommendation

6.1 General Conclusions

The objectives of the study were met through data collected and analysis based on the theoretical framework in Chapter 3.

From the study, it was established that ice was bought every three days where the low season required 45 – 68 kgs for Mrongo and Sena Beach respectively, while high season required 120 kgs for both beaches. Due to lack of insulation of the cooler boxes, there was heat gain from the environment leading to melting of ice faster.

The global horizontal irradiance varied between a low of 5.81 kWh/m^2/day in July and a high of 6.78 kWh/m^2/day in February. The annual average was determined as 6.25 kWh/m^2/day which is significant for meaningful applications. It is evident that solar harvesting is favourable as there is minimal variations in irradiance across the year which would match the solar design without oversizing for low irradiance seasons.

Based on thermal and electrical calculations, it was determined that 2 refrigeration systems would be adequate to meet the cooling loads for Mrongo and 3 for Sena. The electrical energy to be generated required 6 solar panels rated 350 W connected in parallel for Mrongo and 10 for Sena beach. The subsequent designed system ensured that the generated electrical energy would always exceed the demanded electrical energy.

To appraise feasibility of the project, financial indicators were used. It was determined that in Mrongo beach, it would take 2.2 years to recover initial capital cost and a net present valus of USD 6,787.10 in 10 years. It is evident that the project is profitable and can be implemented. On the other hand, at Sena beach the payback period is determined as 2.92 years which is longer compared with that of Mrongo, the net present value was determined as USD 3,153.61. While NPV is lower than that of Mrongo it is positive and therefore means it is a feasible project. The indicators further guides the priority of which project to undertake first that is that of Mrongo.

6.2 Recommendations for Further Work

While the objectives of this study were met successfully, there are some further potential areas of research that would enhance this work. First, due to limitation in research period, it would be of great importance to take measurements of temperature and irradiation considering the once used in the study are 16-year-old dataset and considering climate change impacts, the current values could have significantly changed.

Secondly, design architecture of a solar cooling system has proven to be fundamental in minimising the cost of acquiring the system. While the payback period is still high, the future of solar cooling field is promising and there is opportunity of optimising the designs. Beyond design configuration break through, studying the actual performance of the system under different conditions would lay scope for further research and critique of the progress made.

Third, past studies have focused on scalable techniques from a technical standpoint, ignoring the socioeconomic perspective, which is critical for the long-term viability of rural micro-grids (Chandra et al., 2020). A proposed area of research is to build a holistic design framework that ensures the project's financial viability and created job possibilities in the target locations, all while empowering people through community-level electrification (Chandra et al., 2020).

Last but not least, an attempt to implement the project in totality or partially in either sites would significantly inform design and actual implementation outcomes of this project and other similar ones.

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Appendices

A1: Proposed Bitzer Compressor type

The Figure 5.8 shows the proposed compressor to be used in running the cold storage.

A2: Similarity Index