MAKERERE UNIVERSITY

COLLEGE OF ENGINEERING DESIGN ART AND TECHNOLOGY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

FINAL YEAR PROJECT REPORT

ASSESSMENT AND DESIGN OF SOLAR-POWERED COLD STORAGE SOLUTIONS FOR SMALL-SCALE FISHERIES IN UGANDA: A CASE STUDY OF BWONDHA LANDING SITE

KIGENYI EMMANUEL 22/U/6140

MAIN SUPERVISOR: DR.DONNA LILLIAN NAMUJJU
CO-SUPERVISOR: DR. EDWIN MUGUME

A Final Year Project Report submitted in partial fulfillment of the Requirements for the award of the Degree of Bachelor of Science in Electrical Engineering

June 2026

Declaration

I, **Kigenyi Emmanuel (22/U/6140)**, declare that this project report entitled "Assessment of Solar Powered Cold Solutions for Small Scale Fisheries in Uganda" is my original work and has not been submitted to any other institution for the award of any academic qualification. All sources of information used in this report have been duly acknowledged and referenced.

Kigenyi Emmanuel
22/U/6140

Signature: ______________________________

Approval

This report has been submitted for examination with approval of the following supervisors.

Main Supervisor

Dr. Donna Lillian Namujju
Lecturer
Department of Electrical and Computer Engineering
College of Engineering, Design, Art and Technology
Makerere University

Signature:____________________ Date: 29.06.2026

Co-Supervisor

Dr. Edwin Mugume
Lecturer
Department of Electrical and Computer Engineering
College of Engineering, Design, Art and Technology
Makerere

Signature:____________________ Date: 29.06.2026

Digitisation and Self-Archiving Consent Agreement: Theses

Agreement between Makerere University & Students (Authors of Theses / Dissertations / Reports)

1. The author is a student of Makerere University and author of the thesis / dissertation / report titled:
ASSESSMENT AND DESIGN OF SOLAR-POWERED COLD STORAGE SOLUTIONS FOR SMALL-SCALE FISHERIES IN UGANDA: A CASE STUDY OF BWONDHA LANDING SITE

2. The author grants to the University:
   a. The right to deposit the electronic version of the Thesis / Dissertation / Report into Makerere University Institutional Repositories (Mak IR) or (Mak UD); and
   b. The right to store the thesis / dissertation / report in Mak IR / Mak UD and make it permanently available to the general public via the Internet at no cost to the general public after a grace period (if any is specified). **Choose one of the three options below (c, d, or e):**
   c. The Author may opt for immediate open access to the public ✓
   d. Or Restrict access indefinitely:
   e. Or Restrict access for the specified number of years:
   f. Reason for restriction:

3. The author warrants that to the best of the authors knowledge and belief:
   a. The thesis / dissertation / report is an original work;
   b. The author is the owner of all the intellectual property in the thesis / dissertation
   or
   c. The Author is entitled to deal with the intellectual property in the thesis / dissertation / report by publishing it on the Internet
   d. The Author has the right, power and authority to enter into this Agreement and to grant the University the rights contained in this Agreement; and
   e. The University's use of the thesis / dissertation / report pursuant to this Agreement will not infringe the intellectual property rights of any third party.

4. The Author acknowledges and agrees that the University is not responsible or liable for any breach of the intellectual property rights in the thesis / dissertation / report, in particular any breach of copyright, as a result of the use of the thesis / dissertation / report pursuant to this Agreement.

5. The University acknowledges that the rights granted by the Creator in clause 2 of this Agreement, do not cause any transfer or assignment of any proprietary rights in the intellectual property in the article to the University.

Signed by the Author as confirmation that the Author has read and accepted the terms of this Agreement:

Name: KIGENYI EMMANUEL

College: CEDAT School: SCHOOL OF ENGINEERING

(Tick) Type of Degree: (Undergraduate ✓ / PGD / Masters / PhD), Reg. No.: 22/U/6140

Tel No.: 0763562867 E-Mail: kigenyiemmanuelx@gmail.com

Signature: [signature] Date: 30/06/2026

Supervisor's endorsement: [signature]

Acknowledgement

This work is dedicated to my family for their unwavering support, encouragement, and sacrifices throughout my academic journey. Their belief in my abilities has been a constant source of motivation. I also dedicate this work to my lecturers, supervisors, and colleagues whose guidance and support contributed greatly to the successful completion of this project. Special recognition goes to Dr. Donna Lillian Namujju and Dr. Edwin Mugume for their remarkable supervision, constructive criticism and commendation. Above all I thank God for enabling this great to happen.

Abstract

Small-scale fisheries in Uganda face post-harvest losses estimated at 25–40% of total catch, driven largely by the absence of reliable cold storage infrastructure at off-grid landing sites. This study assesses and designs a solar-powered cold storage system for Bwondha Landing Site in Mayuge District, where approximately 200 fishermen land an average of 1.7 tonnes of fish daily with no functional refrigeration facility. A comprehensive cooling load analysis determined a total cold room requirement of 45.1 kW, dominated by the product load of 40.55 kW. Based on this, a refrigeration system using R-404A refrigerant was designed, yielding a cooling capacity of 56.36 kW and a Coefficient of Performance of 4.53. The supporting solar power system, modelled in HOMER Pro using NASA POWER irradiance data, comprises a 15.5 kWp photovoltaic array, a 48 V / 3500 Ah lithium-ion battery bank, and a 96%-efficient inverter configuration, sized to meet the 12.5 kW electrical load with a minimum of 48 hours of autonomous operation. The cold room, designed in CoolSelector2, measures 5 m × 2 m × 3 m with 100 mm polyurethane insulation and a storage capacity of 3.4 tonnes. System behaviour was validated through MATLAB/Simulink simulation, which confirmed stable AC output across the full PV–battery–inverter–refrigeration chain. Economic analysis demonstrated that the locally fabricated design is approximately 22% cheaper in capital cost than an imported Chinese equivalent, with a payback period of 3.2 years and a 20-year Net Present Value of UGX 1.84 billion. The findings confirm that solar-powered cold storage is both technically feasible and economically viable for small-scale fisheries at Bwondha, offering a sustainable alternative to diesel-based refrigeration and traditional preservation methods.

Table of Contents

List of Figures

List of Tables

List of Acronyms

AI	Artificial Intelligence
BESS	Battery Energy Storage System
BIPV	Building-Integrated Photovoltaics
COP	Coefficient of Performance
CPVT	Concentrating Photovoltaic-Thermal
CSP	Concentrated Solar Power
CWS	Chilled Water Storage
EACREE	East African Centre of Excellence for Renewable Energy and Efficiency
EV	Electric Vehicle
GDP	Gross Domestic Product
IFPRI	International Food Policy Research Institute
LCCA	Life Cycle Cost Analysis
LCOE	Levelized Cost of Energy
LFP	Lithium Iron Phosphate
LiBr-H_2O	Lithium Bromide – Water
LIBs	Lithium-Ion Batteries
LTES	Latent Thermal Energy Storage
MWh	Megawatt-hour
NH_3-H_2O	Ammonia – Water
NGOS	NON Government Organizations
NMC	Nickel-Manganese-Cobalt
NPV	Net Present Value
PCMSh1	Phase Change Material
PVT	Photovoltaic-Thermal (hybrid solar collectors producing both electricity and heat)
R&D	Research and Development
SDG	Sustainable Development Goal
SF	Solar Fraction
TES	Thermal Energy Storage
VCR	Vapor Compression Refrigeration

Chapter 1

Introduction

1.1 Background

Fishing is a critical economic activity and a major source of livelihood for millions of people worldwide, particularly in developing countries. In Uganda, fisheries play a vital role in food security, employment, and income generation, especially among communities located around major water bodies such as Lake Victoria, Lake Albert, Lake Edward, and the River Nile. The fisheries sector contributes significantly to national Gross Domestic Product (GDP), export earnings, and household nutrition through the provision of affordable animal protein. Small-scale fisheries dominate the sector, employing artisanal fishing methods and supporting a large portion of rural and peri-urban populations [2].

Despite its importance, the fisheries sector in Uganda continues to face persistent challenges related to post-harvest handling and preservation of fish. Fish is a highly perishable commodity that begins to deteriorate immediately after harvest due to microbial activity, enzymatic reactions, and improper handling. Effective cold storage is therefore essential to maintain quality, extend shelf life, and preserve the market value of fish. However, it is estimated that post-harvest losses in Uganda's fisheries sector range between 25% and 40% of total catch. These losses translate into significant economic losses for fishermen, traders, and the national economy, while also undermining food security and sustainable resource utilization [2], [3].

One of the primary causes of high post-harvest losses in small-scale fisheries is the lack of reliable and affordable cold storage infrastructure. Most landing sites in rural fishing communities lack access to grid electricity, making conventional refrigeration systems difficult to deploy. As a result, fishermen often rely on traditional preservation methods such as sun drying, smoking, or salting. While these methods reduce spoilage to some extent, they often compromise fish quality, reduce nutritional value, and limit access to higher-value markets that demand fresh or chilled fish. In addition, traditional methods are weather-dependent and may expose fish to contamination, further affecting quality and safety [1], [4].

Where refrigeration is available, it is commonly powered by diesel generators. Although diesel-powered cold storage systems provide cooling capacity, they are associated with high operational costs, fuel price volatility, frequent maintenance requirements, and environmental pollution through greenhouse gas emissions and noise. These factors make diesel-based systems economically unsustainable for many small-scale fishers and cooperatives. The high cost of fuel and equipment often leads to underutilization or complete abandonment of cold storage facilities, perpetuating post-harvest losses and income instability [2], [5].

Uganda is endowed with abundant solar energy resources due to its equatorial location, receiving high levels of solar irradiance throughout the year. This presents a significant opportunity to harness solar energy for productive uses, including cold storage for agricultural and fisheries value chains. Recent advancements in photovoltaic (PV) technology, battery storage systems, and energy-efficient refrigeration have improved the feasibility and reliability of solar-powered cold storage solutions, particularly in off-grid and underserved areas [6].

Solar-powered cold storage systems use photovoltaic panels to generate electricity that powers refrigeration units, often coupled with battery storage or thermal energy storage to ensure continuous operation during periods of low sunlight. These systems offer a clean, renewable, and potentially cost-effective alternative to diesel-powered refrigeration. By reducing dependence on fossil fuels, solar-powered cold storage contributes to environmental sustainability while lowering long-term operational costs. Furthermore, such systems align with Uganda's national renewable energy and climate change mitigation policies, which promote decentralized renewable energy solutions for rural development [4], [7].

Several pilot projects and studies in East Africa have demonstrated the potential of solar-powered cold storage to significantly reduce post-harvest losses, improve fish quality, and increase incomes for small-scale fishers. Improved cold chain infrastructure enables fishermen to store fish for longer periods, access distant markets, negotiate better prices, and reduce the pressure to sell catches immediately at low prices. In addition, reliable cold storage supports value addition, improves food safety, and enhances the competitiveness of locally produced fish in both domestic and export markets [6], [8].

Despite the evident potential, the adoption of solar-powered cold storage solutions among small-scale fisheries in Uganda remains limited. Barriers include high initial capital costs, limited access to financing, inadequate technical skills for system operation and maintenance, and insufficient data on system performance under local climatic and operational conditions. There is also a lack of comprehensive assessments that integrate technical, economic and environmental aspects of solar-powered cold storage systems within Cold storage technology plays an important role in preserving perishable goods such as fruits, vegetables, fish, dairy products, and pharmaceuticals. These products deteriorate quickly when exposed to high temperatures because microbial growth and biochemical reactions accelerate the process of spoilage. Refrigeration systems are therefore essential for slowing these processes and maintaining product quality during storage and transportation.

In many developing countries, however, conventional cold storage facilities are limited due to high electricity costs, unreliable power supply, and insufficient infrastructure in rural areas. As a result, a large portion of agricultural produce is lost before it reaches consumers. These losses significantly affect farmers' incomes and contribute to food insecurity.

1.1.1 Relevance of Solar Cold Storage Technology

Solar cold storage rooms are highly relevant in addressing post-harvest losses in agricultural supply chains. Approximately one-third of food produced globally is lost or wasted annually, and much of this loss occurs during storage due to inadequate refrigeration infrastructure [1].

In tropical regions where temperatures are high, fruits and vegetables deteriorate rapidly after harvesting. Solar cold storage systems allow farmers to store produce for longer periods, enabling them to sell when market prices are more favorable. Cooling slows respiration and enzymatic activity in fresh produce, helping maintain quality and nutritional value.

Additionally, solar cold storage systems are environmentally sustainable because they reduce dependence on diesel generators and grid electricity generated from fossil fuels. This significantly lowers greenhouse gas emissions and operating costs, making the technology suitable for sustainable agricultural development [8].

1.1.2 Emerging Trends in Solar Cold Storage

Technological advancements are improving solar cold storage systems. One key trend is the integration of digital monitoring technologies such as Internet of Things sensors. These sensors track temperature, humidity, and system performance, allowing remote monitoring and improved reliability.

Another trend is the use of advanced energy storage technologies including lithium-ion batteries and phase change materials that store cooling energy. These technologies help maintain stable temperatures even when solar energy is unavailable.

Portable and modular solar cold storage units are also becoming more common. These units are designed to be transported easily and installed in rural markets or farms. Governments and development organizations are investing in renewable energy-based cold chain infrastructure to improve food security and reduce food waste [3].

1.1.3 Solar Cold Rooms

Solar cold storage rooms have emerged as a sustainable solution to this challenge. These systems use solar photovoltaic panels to generate electricity that powers refrigeration systems used to cool insulated storage rooms. Because they rely on renewable energy, solar cold storage systems can operate in off-grid or energy-deficient regions where conventional electricity supply is unreliable. The technology has therefore gained increasing attention as an effective method for reducing post-harvest losses and improving agricultural productivity [9].

1.2 Problem Statement

Despite being a key livelihood activity, small-scale fisheries in Uganda face significant post-harvest losses due to inadequate cold storage infrastructure. Most fishermen rely on traditional methods such as sun drying or smoking, which reduce fish quality and market value. Limited access to grid electricity and the high cost and environmental impact of diesel generators exacerbate the problem. As a result, fishermen lose a significant portion of their catch, leading to reduced incomes, food insecurity, and wastage. Therefore, there is a need to assess the feasibility and performance of solar-powered cold storage systems as a sustainable alternative to conventional methods.

1.3 Project Objectives

1.3.1 Main Objective:

To design a reliable, and efficient solar-powered cold storage system that significantly reduces post-harvest losses and increases the income of small-scale fishers in Uganda.

1.3.2 Specific Objectives:

1. To conduct a comprehensive technical assessment of the site, including solar irradiation, ambient temperatures, and daily/seasonal fish catch volumes.
2. To determine the optimal storage capacity, cooling load,and electrical load required to minimize fish spoilage.
3. To design the standalone Solar PV system (panels, battery storage, MPPT, inverter) to reliably meet the determined cold storage electrical load.
4. To design the solar cold Room in coolselector2 software

1.4 Justification

1.4.1 Reduction of Post-Harvest Fish Losses

Fish is highly perishable and requires immediate preservation after harvest. In Uganda, the fisheries sector experiences post-harvest losses of about 10–20%, largely due to limited access to cold storage and poor preservation methods. Solar cold storage rooms can:

1. Maintain low temperatures that slow bacterial growth and spoilage.
2. Preserve fish quality for longer periods.
3. Reduce waste and increase the amount of fish reaching markets.

The study helps determine how effective solar cold storage can be in reducing these losses in local fishing communities.

1.4.2 Improvement of Income for Fisherfolk

Fishing supports the livelihoods of over 5.3 million Ugandans and employs more than 1.2 million people directly. When fish spoils quickly:

1. Fishermen are forced to sell at very low prices.
2. Traders and fishermen lose potential income.

Solar-powered cold storage enables fish to be stored longer, allowing:

1. Better bargaining power in markets
2. Access to distant markets
3. Increased profitability for fishermen and traders.

Studies have shown that improved cold storage and ice access can reduce losses and significantly increase income for fishing households.

1.4.3 Reliable Preservation in Off-Grid Fishing Communities

Many fishing communities around lakes such as Lake Victoria, Lake Kyoga, and Lake Albert lack reliable grid electricity. Solar cold storage systems are significant because they:

1. Use renewable solar energy available in rural areas.
2. Operate independently from unreliable power grids.

3. Provide continuous cooling even in remote landing sites. Research helps determine the technical feasibility and reliability of solar refrigeration systems in these conditions

1.4.4 Enhancement of Food Security and Nutrition

Fish is a major source of protein and essential nutrients for many Ugandan households. By reducing spoilage:

1. More fish becomes available for consumption.
2. Prices become more stable.
3. Food supply chains become more efficient.

Solar-powered cold chains therefore contribute to improved national food security and nutrition.

1.4.5 Environmental Sustainability

Traditional preservation methods may rely on:

1. Diesel generators
2. Firewood smoking
3. Ice transported long distances

Solar cold storage:

1. Uses renewable energy
2. Reduces greenhouse gas emissions
3. Decreases reliance on fossil fuels

Studying these systems supports the transition toward clean energy solutions in the fisheries sector.

1.4.6 Development of the Fisheries Value Chain

Cold storage facilities improve the entire fish supply chain by:

1. Maintaining fish quality from landing sites to markets
2. Supporting fish processing and export industries
3. Increasing market competitiveness.

The study can help identify optimal locations, design considerations, and operational models for solar cold storage rooms in fisheries communities.

1.4.7 Policy and Infrastructure Planning

Research findings can help:

1. Government agencies
2. NON Government Organizations (NGOS)
3. Investors

make informed decisions regarding:

1. Cold chain infrastructure development
2. Renewable energy investments
3. Fisheries sector modernization.

This study provides data for evidence-based policy and sustainable fisheries management.

1.5 Significance of the Study

Solar-powered cold storage solutions offer an environmentally friendly and cost-effective approach to addressing post-harvest losses in fisheries. This assessment aligns with Uganda's renewable energy and food security goals by promoting sustainable energy use in the fisheries value chain. The results will guide policymakers, investors and local entrepreneurs in scaling up the solar cold chain infrastructure, improving livelihoods, reducing food waste, and improving the competitiveness of Uganda's fish exports.

Chapter 2

Literature Review

2.1 Introduction

The fisheries sector in East Africa plays a critical role in food security, employment, and rural income generation. In Uganda alone, over 1.5 million people depend on fisheries directly or indirectly, contributing significantly to both nutrition and export earnings [1]. Despite this contribution, the sector continues to face significant post-harvest losses due to inadequate cold storage infrastructure, unreliable grid electricity, and dependence on traditional preservation techniques such as sun drying and smoking. This review synthesizes existing research on solar-powered cold storage applications in Uganda and East Africa, focusing on technological, socio-economic, and policy dimensions.

1. State of Fisheries and Post-Harvest Losses in Uganda and East Africa Post-harvest fish losses in East Africa are estimated at 25–40% of total catch, primarily caused by microbial spoilage, mechanical damage, and poor handling [2]. Uganda's fisheries, particularly around Lake Victoria, Lake Albert, and Lake Edward, are dominated by small-scale fishers who lack access to reliable refrigeration [6]. Traditional preservation methods reduce losses but often compromise quality and market value. [8] emphasizes that poor cold chain management has not only economic but also food security implications, especially in remote fishing communities with limited energy access.

2. Technological Developments in Solar-Powered Cold Storage Advancements in photovoltaic (PV) and energy storage technologies have made solar-powered cold rooms increasingly viable in off-grid contexts. Studies in Kenya and Uganda [3] show that solar refrigeration systems using PV-battery hybrids can maintain optimal fish storage temperatures between 0°C and 4°C for up to 24 hours without sunlight. [6] found that solar-powered cold rooms reduced spoilage by 60%, while [2] demonstrated that integrating Phase Change Material (PCMSh1) improved thermal stability. [7]highlighted the potential of locally fabricated solar systems using affordable components for rural fisheries.

3. Socio-Economic and Environmental Implications The introduction of solar cold storage has demonstrated notable improvements in livelihoods. [1] reported that solar-powered cold chains increased fisher income by 30% through improved product quality and access to distant markets. Solar systems also reduce reliance on diesel generators, thereby cutting operational costs and carbon emissions [8]. However, adoption remains limited due to high upfront investment and maintenance costs. [5] found that cooperative ownership models could enhance sustainability and affordability among Lake Victoria fishing groups.

4. Policy, Institutional, and Market Frameworks Uganda's Renewable Energy Policy [4] encourages decentralized solar systems for productive uses such as fish preservation. Regional initiatives like East African Centre of Excellence for Renewable Energy and Efficiency (EACREE) have promoted renewable energy research and technology transfer across East Africa. Nevertheless, inadequate financial mechanisms and weak policy enforcement limit scalability. [2] and [1] both emphasize the need for targeted subsidies and training programs to build local technical capacity.

5. Challenges, Research Gaps, and Opportunities Despite clear potential, key challenges persist, including limited technical expertise, inadequate financing models, and lack of performance monitoring data. There is also a gap in integrating digital monitoring systems for temperature regulation. Emerging opportunities include hybrid PV-battery-PCMSh1 systems and community-based financing mechanisms. Future research should focus on the life cycle cost analysis (LCCA) of solar systems under Uganda's climatic conditions and explore integration with digital tracking tools for improved efficiency and traceability.

2.2 Solar Energy as an Energy Resource

Solar energy, derived from the Sun's radiation, stands as one of the most abundant, widely distributed, and sustainable renewable energy resources available on Earth. It encompasses PV conversion to electricity and solar thermal applications for heat or power generation. As global energy demand rises and fossil fuel depletion alongside climate concerns intensify, solar energy has emerged as a cornerstone for transitioning to low-carbon systems [10], [11].

Literature highlights solar's vast technical potential, far exceeding current and projected global energy needs. Theoretical global solar resource averages around 168 W/m² at the surface, with technical potentials estimated in the range of tens to hundreds of Terawatts electric (TWe), constrained by land use, conversion efficiencies, and infrastructure [12]. Recent assessments project solar PV capacity growing from 1053 GW in 2022 to over 11,000 GW by 2050 under optimistic scenarios, potentially supplying 25% of global electricity [10], [13].

2.2.1 Types and Technologies

1. PV Systems Dominant in deployments, PV converts sunlight directly to electricity using semiconductor materials. Crystalline silicon (mono- and polycrystalline) remains prevalent, with efficiencies of 20–25%. Emerging advancements include perovskites, tandem cells (silicon-perovskite reaching 34.85% lab efficiency in 2025), thin-film, and bifacial panels [14], [15]. Global installed PV capacity reached 1419 GW by 2023, contributing 36.7% of renewable capacity additions [16].

2. Solar Thermal Systems: These capture heat for direct use (e.g water heating) or electricity via Concentrated Solar Power (CSP) technologies like parabolic troughs. CSP enables dispatchable power with thermal storage, though it has lower installed capacity than PV [11], [17].

3. Hybrid and Integrated Systems: Photovoltaic-Thermal (hybrid solar collectors producing both electricity and heat) (PVT) hybrids produce electricity and heat simultaneously, boosting overall efficiency to 50–80%. Building-Integrated Photovoltaics (BIPV) and passive solar designs further expand applications [18].

2.2.2 Performance and Advancements

Key metrics include efficiency, Levelized Cost of Energy (LCOE), and capacity factors. PV LCOE has fallen dramatically, often below $0.02–0.11/Kilowatt-hour (kWh) in optimal conditions, making it competitive with or cheaper than fossil fuels in many regions [11], [19]. Recent reviews note continuous efficiency gains through material innovations and system optimizations [14], [20].

Global installations hit record levels: 597 GW added in 2024 (33% growth), with projections for 655 GW in 2025 and continued double-digit growth toward 930 GW annually by 2029 under medium scenarios [21].

2.2.3 Economic, Environmental, and Policy Impacts

Solar energy significantly reduces CO_2 emissions (0.5 tons per MWh displaced), supporting the United Nations (UN) Sustainable Development Goals, particularly SDG 7 (affordable clean energy) [22].

Economic benefits include job creation, energy security, and decreasing costs via economies of scale [10], [23].

Policies such as feed-in tariffs, subsidies, tax incentives, and auctions have driven adoption, with leaders like China (570 GW installed), USA, Japan, Germany, and India [24].

Challenges include intermittency (addressed via storage and hybrids), land requirements, supply chain dependencies, and grid integration [11], [25].

2.2.4 Challenges and Future Directions

Barriers encompass initial costs (though they decrease), intermittency, material supply (e.g rare earths), and recycling needs [25].

Future trends focus on perovskite-tandem cells, AI-optimized systems, floating PV, agrivoltaics, and large-scale storage integration to enhance reliability [14], [15].

Literature consensus projects solar as a leading source by mid-century, potentially supplying a major share of global energy under accelerated deployment [10], [26].

2.2.5 Conclusions

The abundance of solar energy, the rapid decline in cost, and the technological maturity position it as a crucial renewable resource for sustainable development. PV leads growth, complemented by thermal and hybrid innovations. Continued policy support, Research and Development (R&D), and infrastructure scaling are essential to realize its full potential in mitigating climate change and ensuring energy access.

2.3 Batteries for Energy Storage

Batteries serve as a critical electrochemical energy storage technology, converting chemical energy into electrical energy and vice versa through reversible reactions. They enable energy shifting, grid stabilization, renewable integration, and electrification across sectors like transportation, renewables, and stationary applications. Lithium-Ion Batteries (LIBs) dominate due to high energy density, efficiency, and cycle life, but emerging alternatives address sustainability, cost, and resource concerns [27], [28].

The global battery market, particularly for energy storage, has expanded rapidly. In 2025, lithium-ion battery deployment reached unprecedented levels, with utility-scale additions contributing to record growth. Stationary Battery Energy Storage System (BESS) saw pack prices drop to around $70/kWh for stationary use, making them the cheapest lithium-ion segment [29], [30]. Cumulative global utility-scale battery capacity exceeded 124 GW by late 2024–early 2025, with projections for continued exponential scaling to support renewable penetration [31], [32]. Figure 2.1 shows a battery bank

2.3.1 Dominant Technologies and Advancements

Lithium-Ion (Li-ion) remains the workhorse for both Electric Vehicle (EV)s and grid storage, offering energy densities of 150–250 Wh/kg, efficiencies of 85–95%, and cycle lives of 1,000–10,000. Chemistries include Nickel-Manganese-Cobalt (NMC), LFP, and high-nickel variants. Recent advancements focus on silicon-enhanced anodes, high-nickel cathodes, and sustainable materials to

Figure 2.1: Battery Bank.

boost energy density and reduce costs [27], [33]. In 2025, Lithium-Ion (Li-ion) BESS achieved breakthroughs in quasi-solid-state configurations for improved safety and longevity [34].

2.3.2 Emerging and Alternative Technologies

1. Sodium-Ion Batteries Resource-abundant and low-cost alternatives, with manganese-rich cathodes and hard-carbon anodes enabling grid-scale viability, including low-temperature performance down to –40^{o}C [34].

2. Solid-State Batteries Replace liquid electrolytes with solid ones for higher safety, energy density, and stability; quasi-solid and full solid-state variants advanced significantly in 2025 [35].

3. Other Post-Lithium Options Metal-air (e.g zinc-air, lithium-sulfur), flow batteries, and zinc-based systems offer potential for long-duration storage, though they face scalability and efficiency hurdles [28], [36]. Hybrid systems combining batteries with supercapacitors or other storage enhance power response and lifespan [37].

2.3.3 Performance Metrics and Applications

Key metrics include energy/power density, round-trip efficiency (typically 85–95% for Lithium-Ion (Li-ion)), cycle life, cost (levelized cost of storage falling rapidly), and safety. Lithium-Ion (Li-ion) excels in short- to medium-duration applications (1–8 hours), supporting peak shaving, frequency regulation, and solar/wind firming [29], [38]. Grid-scale BESS now provide ancillary services, with deployments enabling higher renewable shares by mitigating intermittency. In 2025, global energy storage additions (excluding pumped hydro) reached 92 GW/247 GWh, a 23% increase from 2024, driven by China (>50%) and the US [39]. Battery storage supports decarbonization, with lifecycle assessments showing reduced emissions when paired with renewables [40].

2.3.4 Economic, Environmental, and Policy Impacts

Costs have plummeted stationary Li-ion pack prices fell 45% year-over-year in 2025, reaching $70/kWh, with full systems at $125/kWh in some markets [29]. The global Lithium-Ion (Li-ion) market exceeded $150 billion in 2025, up >20% from 2024 [41]. Environmentally, batteries reduce fossil reliance but raise concerns over mining, recycling, and end-of-life management; sustainable practices and second-life applications are gaining traction [27], [42].

Policies (subsidies, tax credits, mandates) in the US, EU, China, and emerging markets drive adoption. Recycling advancements and supply chain diversification mitigate risks [43].

2.3.5 Challenges and Future Directions

Challenges include supply chain vulnerabilities (lithium, cobalt), thermal runaway risks, degradation over cycles, and recycling infrastructure gaps [27], [44]. Intermittency for long-duration storage (>8–10 hours) favors alternatives like flow or sodium-ion. Future trends emphasize solid-state commercialization, sodium-ion scaling, AI-optimized management systems, and integration with renewables for net-zero goals. By 2030–2035, cumulative BESS capacity could reach terawatt-hour scales, with Lithium-Ion (Li-ion) supplemented by diverse chemistries [32], [45].

2.4 Solar Cold Room

Solar cold storage rooms, also known as solar-powered cold rooms or solar refrigeration units, utilize solar energy—primarily PV or solar thermal—to maintain low temperatures (typically 0˜15^{o}C) in insulated enclosures for preserving agricultural produce, fish, dairy, or other perishables. These systems are particularly valuable in off-grid or unreliable-grid regions, where they help mitigate 20–50% post-harvest losses common in developing countries and reduce energy costs and emissions compared to conventional refrigeration [46], [47]. The literature on solar cold storage has grown substantially since the early 2010s, fueled by declining PV costs, advancements in Phase Change Material (PCMSh1), and emphasis on sustainable food systems. Key reviews distinguish between PV-driven Vapor Compression Refrigeration (VCR) systems, which dominate due to higher Coefficient of Performance (COP), and solar thermal absorption/adsorption systems, which leverage direct heat utilization [48], [49]. Hybrid designs incorporating Thermal Energy Storage (TES) are increasingly prominent for addressing solar intermittency [50]. Figure 2.2 shows a cold room

2.4.1 Types of Solar Cold Storage Systems

1. PV-Driven Systems These employ PV panels to generate electricity for conventional VCR units, often using DC compressors for improved efficiency without inversion losses. This configuration is favored for small-to-medium scales because of modularity, COP values typ-

Figure 2.2: Cold Room.

ically 2.5–4.0, and compatibility with battery or TES backups [48]. Recent studies emphasize PV-PCMSh1 integration to reduce panel overheating and enhance overall performance, with reported energy use as low as 0.01–0.02 Wh/kg/day for produce [50].

2. Solar Thermal Systems These rely on collectors (flat-plate, evacuated-tube, or concentrating) to drive absorption (e.g., LiBr-H_2O or NH_3-H_2O) or adsorption cycles. Single-effect absorption chillers require generator temperatures of 70–90°C and achieve thermal COPs of 0.5–0.8, lower than VCR but with higher solar energy utilization and minimal electricity needs [49]. Photovoltaic-Thermal (hybrid solar collectors producing both electricity and heat) (PVT) hybrids improve total efficiency to 50–60% by producing both electricity and heat [49].

3. Hybrid and Portable Variants Modern systems frequently combine PV-VCR with thermal absorption, grid backup, or PCMSh1 storage. Portable units (2–10 metric tons) suit rural applications [47], [51].

2.4.2 Performance Metrics

Performance is assessed using COP, Solar Fraction (SF), temperature stability, energy consumption, and shelf-life extension. PV-VCR systems commonly exceed COP of 3, with SF up to high values in optimized setups. Absorption systems deliver thermal COPs of 0.5–0.91 and SF around 50% annually when integrated with storage tanks [49]. Notable examples include:

1. A 3.5 kW solar absorption system tested in tropical conditions using evacuated-tube collectors and PV assistance [52].

2. PCMSh1-enhanced systems yielding 8% COP improvement and 12% power reduction; computational fluid dynamics models predict 5–15% gains with optimized PCMSh1 placement [50].

3. Brine or water TES sustaining 7^{o}C for over 12 hours, with PCMSh1 extending cooling to 16–17 hours [50].

Storage at 5–10°C (chilled) or 1–8°C (PCMSh1-integrated) extends shelf life up to fourfold, reduces weight loss threefold, and preserves nutritional quality (e.g improved vitamin C retention) [46], [53].

2.4.3 Integration with Thermal Energy Storage

TES overcomes solar variability. Cold TES options include chilled water storage, ice TES (high latent heat of 334 kJ/kg), and latentTES via PCMSh1(e.g eutectics). PCM integration in evaporators or walls provides uniform temperature control and 6–10% efficiency gains over battery-only systems [50], [54]. Hybrid latent-electrochemical storage shortens payback periods and improves net present value significantly [50]. Off-grid PV setups with batteries and cold-water tanks achieve 6.73–10.5% higher efficiency [50].

2.4.4 Economic, Environmental, and Social Impacts

Deployments demonstrate strong viability. In northeast Nigeria, solar cold storages increased horticulture sales by 69%, net revenue share by 13 percentage points, extended shelf life by 7–11 days, and reduced losses by 4.7–11.2 percentage points, with nutritional preservation and feasible payback within 10 years [46]. In India, 5–10 MT PV systems yield annual CO_2 reductions of 623 kg and payback under 3 years [50]. Techno-economic studies favorPV-TES over battery-only configurations, with levelized cost of energy as low as 0.02 $/kWh [50]. Environmentally, solar systems reduce life-cycle emissions by over 45% versus grid/diesel alternatives [55]. Socially, they enable smallholder value addition and market access [47], [51].

2.4.5 Challenges

High initial costs (30–50% above conventional), PCMSh1 degradation, dust on panels, sizing mismatches, and lower absorption COP in humid tropics persist as barriers [49], [50].

2.4.6 Future Directions

Research focuses on PCMSh1 stability, AI/IoTcontrols, multi-effect absorption, and concentrating PVT hybrids. Decentralized mini-grids and subsidies in Africa/Asia accelerate adoption, with PV cost trends projecting economic superiority by 2030 [56].

2.4.7 Conclusions

Solar cold storage rooms have evolved into reliable, impactful solutions with COP 0.5–4+, effective TES , paybacks of 2–10 years, and benefits for food security and emissions. PV -VCR with PCMSh1-TES suits small rural applications, while solar thermal fits larger scales. Further cost reductions and standardization will drive scaling in high-loss regions.

Table 2.1: Summary of Key Regional Studies

Focus Area	Key Findings	Limitations	Author	Year
Solar fish dryers and cold rooms (Uganda)	Improved shelf life by 40%; limited scalability due to cost.	High capital cost and limited training.	Nabwire, S.	2022
PV cold storage (East Africa)	Maintained 0–4°C; reduced spoilage by 60%.	Lack of local maintenance capacity.	Oyelami, A.	2020
Locally fabricated solar cold rooms (Uganda)	Feasible for small cooperatives; cost-effective.	Limited long-term data.	Musinguzi, T.	2022
Community solar financing (Lake Victoria)	Enhanced affordability and sustainability.	Dependent on cooperative governance.	Okello, D.	2023

2.5 Research Gaps

1. Local operating data are insufficient
2. Economic feasibility is not fully established
3. Comparative studies are still few

2.6 Summary

This chapter reviewed existing literature on solar energy as a renewable resource, battery energy storage technologies, and solar-powered cold storage systems, with particular attention to applications in fisheries and agricultural value chains in Uganda and East Africa. The review confirmed that post-harvest fish losses in the region remain high, estimated at 25–40% of total catch, driven largely by inadequate cold storage infrastructure and unreliable or absent grid electricity at landing sites such as Bwondha. Photovoltaic technology was shown to be a mature and increasingly affordable resource, while lithium-ion batteries remain the dominant electrochemical storage option. PV-driven Vapor Compression Refrigeration systems were identified as a proven means of reducing spoilage by as much as 60% and improving fisherfolk incomes by up to 30%. The regional case studies summarized in Table 2.1 confirmed the technical feasibility of locally fabricated solar cold rooms. The identified gaps directly motivate the methodology adopted in Chapter 3.

Chapter 3

Methodology

3.1 Study Site Description

Located in Bwondha Parish of Bunya County, 80 km from Iganga and surrounded by the South Busoga Forest Reserve, Bwondha is the most productive landing in the district. About 200 fishermen are found here, of whom 38 are boat owners and 80 are gear owners.

A total of 58 boats are on record at Bwondha, of which 36 are active fishing units and 8 are outboard-powered transport craft. The remaining 14 boats are inactive at present. Crew number 3 to 4 members per boat, and operate with between 2 to 10 nets. The fishery is primarily for Nile perch, and net sizes are thus of the larger 8" to 10" (stretched mesh) size. Angling, seining, and longlining are also quite evident here.

Average daily catch is estimated at 1.7 tonnes, consisting mainly of Nile perch and some tilapia. Fish is marketed at Iganga, Mbale, Tororo, and Pallisa by about 130 fish traders. Beach prices for fresh fish at the time of visit were UShs 150/kg for tilapia and UShs 100/kg for Nile perch. Smoked Nile perch were reportedly fetching the rather high price of UShs 370/kg.

About two-thirds of the Bwondha catch is processed on site. Improved smoking kilns number 44 of which 10 are non-operational. But smoking itself is not effective for preservation for it lowers fish quaity. No proper stores are available and processors have to use compartments in the smoking kilns when it proves necessary to keep fish. The Landing Site is shown in Figure 3.1 and Figure 3.2

3.2 System Architecture

The system architecture shown in Figure 3.3 illustrates the configuration and energy flow of the proposed solar-powered cold room. The system is designed to provide reliable refrigeration for fish preservation using solar energy as the primary power source, with battery storage ensuring continu-

Figure 3.1: Bwondha Landing Site [1].

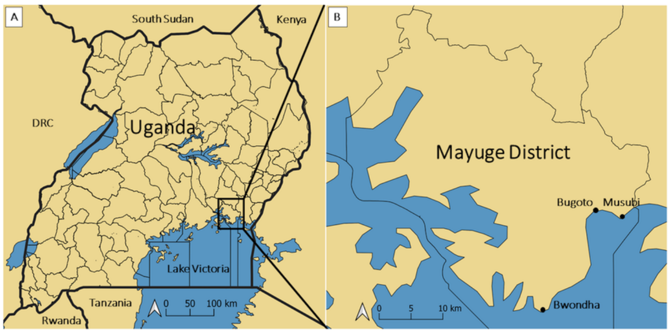

Figure 3.2: Location on the Map [1].

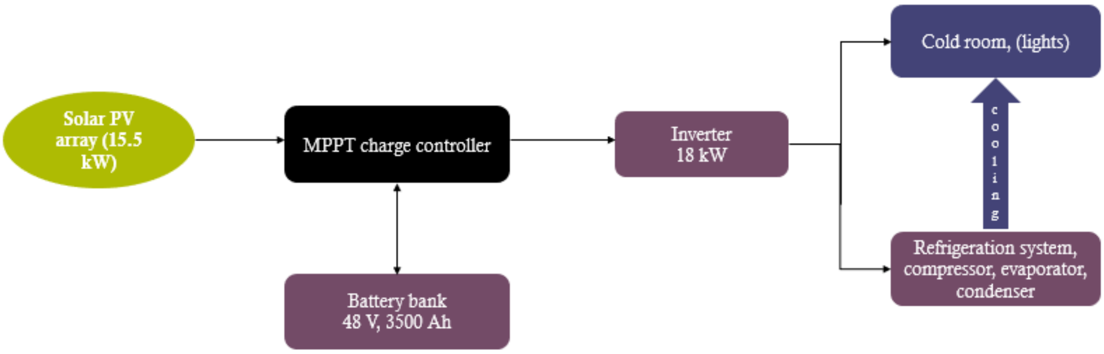

Figure 3.3: System Architecture.

ous operation during periods of low solar irradiance and at night.

The system consists of five major components: the solar photovoltaic (PV) array, Maximum Power Point Tracking (MPPT) charge controller, battery bank, inverter, and refrigeration load.

Solar PV Array: The solar PV array has a total installed capacity of 15.5 kW and serves as the primary energy generation source. The photovoltaic modules convert solar radiation into direct current (DC) electrical energy. During daylight hours, the array supplies power to the cold room while simultaneously charging the battery bank through the MPPT charge controller.

Charge Controller: The MPPT charge controller regulates the power generated by the solar panels and ensures that the PV array operates at its maximum power point under varying weather conditions. This improves energy harvesting efficiency and protects the battery bank from overcharging and excessive discharge. The controller acts as the interface between the PV array and the energy storage system.

Battery Bank: A 48 V, 3500 Ah battery bank is incorporated to store excess electrical energy generated during periods of high solar availability. The stored energy is used to power the refrigeration system and lighting during nighttime or cloudy conditions when solar generation is insufficient. The battery bank enhances system reliability and ensures uninterrupted cold storage operation.

Inverter: The stored DC power from the battery bank and PV system is converted into alternating current (AC) by an 18 kW inverter. The inverter supplies electrical power at the required voltage and frequency for the cold room equipment. The inverter capacity is selected to accommodate the starting and running loads of the refrigeration compressor as well as auxiliary loads such as lighting.

Cold Room Loads: The inverter supplies power to two main load categories: Cold Room Lighting – Provides illumination for operational activities such as loading, unloading, inspection, and maintenance within the cold room. Refrigeration System – Comprises the compressor, condenser, evaporator, and associated control equipment responsible for maintaining the desired storage temperature. The refrigeration cycle continuously removes heat from the cold room, ensuring that fish products remain at the required preservation temperature.

System Operation: During daytime operation, the solar PV array generates electricity that is regulated by the MPPT charge controller. The generated power is used to meet the refrigeration and lighting demands while simultaneously charging the battery bank. When solar energy is unavailable or insufficient, the battery bank supplies stored energy through the inverter to maintain continuous operation of the refrigeration system. This architecture ensures a sustainable, reliable, and environmentally friendly cold storage solution suitable for small-scale fisheries and off-grid applications.

3.3 Cooling Load Calculation

3.3.1 Transmission Load Calculation

In the design of this cold storage system, polyurethane insulation with a thickness of 133 mm and a thermal conductivity of 0.022 W/m·K was used due to its excellent capability in minimizing heat transfer. Additionally, the structure incorporates materials such as stainless steel and aluminum. Stainless steel, with a thickness of 70 mm and a thermal conductivity of 14.4 W/m·K, is used in several parts of the structure because, despite having lower conductivity compared to aluminum, its durability and strength make it suitable for specific structural applications. Meanwhile, aluminum, with a thickness of 10 mm and a very high thermal conductivity of 150 W/m·K, is predominantly used in areas that require strength while also needing boosted heat transfer (Arif Budiyanto et al., 2024).

The heat flux through the wall is calculated using the following equation:

$$q_{\text{wall}} = \frac{A \cdot \Delta T}{\frac{1}{h_1} + \frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{L_3}{k_3} + \frac{1}{h_2}}, \tag{3.1}$$

where q is the heat flux (W/m^2), ΔT is the temperature difference (K), L is the thickness (m), h is the convective heat transfer coefficient ($W/m^2 \cdot K$), and K is the thermal conductivity (W/m·K).

3.3.2 Infiltration Load Calculation

The door opening has the same dimensions as the door itself, which is 2 meters by 1.653 meters, resulting in a total area of 3.306 square meters. The door is opened five times per hour due to product retrieval activities and frequent movement of workers entering and exiting the room. Each time the door is opened, it takes approximately 10 seconds to open and close, and the door remains open for 5 minutes in the cold room.

$$D_t = \frac{(P\theta_p + 60\theta_o)}{3600\theta_d}, \tag{3.2}$$

where, D_t refers to the decimal portion of the time when the door remains open, while P represents the number of door passages that happen. θ_p is the door opening-closing time, measured in seconds per passage, and θ_o is the duration for which the door remains open, measured in minutes. θ_d indicates the daily time (or other relevant period) used in the calculation, measured in hours. The total infiltration load for the cold storage compartment is calculated using the following equation:

$$q_t = VA(h_i - h_r)\rho_r D_t, \tag{3.3}$$

where q_t is the average cooling load (kW), V is the average air velocity (m/s), A is the area of the door opening (m^2), h_i and h_r are the enthalpies of the incoming air and the indoor air, respectively (kJ/kg), ρ_r is the density of the indoor air (kg/m^3), and D_t is the decimal value of the time the door remains open. In this calculation, the ambient temperature is 35°C with a relative humidity (RH) of 90%, while the temperature in the cold room is -5°C with the same RH.

3.3.3 Product Load Calculation

The product load in the cold room, is calculated based on the heat released which includes both sensible and latent heat, as the temperature decreases from 30°C to -5°C. The types of fish cooled in this room consist of various marine species, such as Nile perch, Tuna and Tilapia. However, for the purpose of heat load calculation, the data used are based on Tilapia, as it is the most frequently and abundantly stored species in the cold storage. According to the attached Table, the specific heat and latent heat values for Tilapia are as follows: density of 1030 kg/m^3, freezing point of -2°C, specific heat capacity above the freezing point of 3.43 kJ/kg·K, latent heat of fusion of 227 kJ/kg, and specific heat capacity below the freezing point of 2.19 kJ/kg·K (Budiyanto et al., 2023).

To calculate the product volume, the dimensions used are 1 meter in length, 0.75 meters in width, and 0.8 meters in height, resulting in a volume of 0.6 m^3. Using the density of Tilapia, which is 1030 kg/m^3, the mass of fish per rack is calculated to be 618 kg. With a total of 16 racks, the total mass of Tilapia is approximately 10 tons. The sensible heat product load in the freezer room (Q_{psa}) is calculated using the following equations:

$$q_1 = m \times C_p \times (\Delta T), \tag{3.4}$$

$$q_2 = m \cdot h_{lf}, \tag{3.5}$$

where m is the mass of the product (kg), C_p is the specific heat capacity (kJ/kg·K), ΔT is the temperature change (K), and h is the latent heat of fusion (kJ/kg).

3.3.4 Occupant Load Calculation

The number of people present in the cold storage room affects both the sensible and latent heat loads. In the cold room, 2 individuals are performing light work or walking slowly, with each person generating 90 W of sensible heat and 95 W of latent heat. In the cold room, with a working duration of 5 hours per day, the Cooling Load Factor (CLF) is 0.04 (as indicated in Tables 4.5 and 4.6 of the Cooling and Heating Load Calculation Manual) (Dr. William Rudoy & Joseph F. Cuba, 1991) [57].

$$q_s = q_{s/person} \times \text{No. of People} \times \text{CLF}, \tag{3.6}$$

$$q_l = q_{l/person} \times \text{No. of People}. \tag{3.7}$$

3.3.5 Lighting Load Calculation

The lighting load calculation in the freezer involves several parameters to determine the total power consumed by the lighting system. In this case, the input power per lamp is 40 W, with an operational time (t_{Lights}) of 10 hours per day. The number of lamps used is 2, with a usage factor (F_u) of 0.75, indicating the fraction of power utilized by the lamps in a system equipped with ducted ventilation and return air. Additionally, the special ballast factor (F_s) is 1.20, referring to the additional factor for fluorescent lamps, based on Table 4.1 of the Cooling and Heating Load Calculation Manual, with 2 lamps per fixture.

For the cooling load calculation, a Cooling Load Factor (CLF) of 0.89 is used, calculated based on $a = 0.75$ and $b = C$, with an operational time of 10 hours, in accordance with Table 4.4 and supported by Table 4.2 and Table 4.3 in the Cooling and Heating Load Calculation Manual. The total lighting load ($q_{s,\text{lamp}}$ and n as the number of lamps) can be calculated using the following formula:

$$q_s = q_i \times F_u \times F_s \times \text{CLF}, \tag{3.8}$$

$$q_{s,\text{lamp}} = n \times q_s, \tag{3.9}$$

3.3.6 Fan Motor Load Calculation

The heat load calculation for the evaporator fan motors in the freezer room involves the number of fans used and the power output of each fan. In this case, there are 2 fans, each with a power rating of 439 W (as referenced in Table 4.10, ASHRAE). The Cooling Load Factor (CLF) applied for the heat load calculation is 0.65, based on Table 4.11 of the Cooling and Heating Load Calculation Manual, ASHRAE.

$$q_s = \frac{P_{motor}}{\eta} \times F_i \times \text{CLF}, \tag{3.10}$$

where, P representing the fan power,η represents motor efficiency, F_i as the correction factor corresponding to the operational conditions of the fan, and CLF as the Cooling Load Factor accounting for the duration of operation, this calculation is essential to determine the heat contribution from the evaporator fan motors to the total heat load that must be managed by the cooling system in the freezer room, where n denotes the number of fans.

$$q_{\text{fan}} = n \times q_s. \tag{3.11}$$

The total cooling load in the cold storage room is calculated by summing all components that contribute to the internal heat load, as shown in (3.12):

$$q_{\text{total}} = q_{\text{transmission}} + q_{\text{infiltration}} + q_{\text{product}} + q_{\text{occupants}} + q_{\text{lighting}} + q_{\text{fan}}. \tag{3.12}$$

3.4 Solar PV Sizing

The energy balance of the system can be established using the correlation [58];

$$E_{el} = \frac{Q_T}{\text{COP}} + (P_{off} \cdot t) \quad , \tag{3.13}$$

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 total solar PV energy production is determined as,

$$E_{PV} = \frac{P_{mod} \cdot \eta_{mod} \cdot H \cdot N}{G_{src}} \quad , \tag{3.14}$$

where E_{PV} is the generated PV energy, P_{mod} is the PV power output, η_{mod} is the module efficiency, H is the global solar irradiation, G_{src} is the irradiance at standard test conditions and N is the number of solar panels.

Module efficiency is established as,

$$\eta_{mod} = \eta_{ref}\left(1 - \gamma \cdot (T_{mod} - 25)\right) \quad , \tag{3.15}$$

where η_{ref} is the rated module efficiency, γ is the temperature coefficient.

The module operating temperature can be estimated as,

$$T_{mod} = T_{amb} + \left[\frac{(NOCT - 20)}{0.8} \cdot \frac{G}{1000}\right] \quad . \tag{3.16}$$

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

$$E_{PV} > E_{el} \quad . \tag{3.17}$$

3.5 Economic Analysis

Economic analysis in this study is based on Simple Payback Period (SPP) and Net Present Value (NPV).

Simple payback period is given by:

$$\text{SPP} = \frac{\text{Initial Investment}}{\text{Annual Savings}} \quad . \tag{3.18}$$

NPV is given by:

$$\text{NPV} = \sum_{t=1}^{n} \frac{FV_t}{(1+r)^t} - \text{Capital Cost} \quad . \tag{3.19}$$

3.6 Summary

This chapter presented the methodological approach used to design and assess the solar-powered cold storage system proposed for Bwondha Landing Site. The study site was first characterized in terms of its fishing activity, fleet composition, daily catch volumes, and existing preservation practices, establishing the baseline demand the system is intended to meet. A system architecture comprising a solar PV array, an MPPT charge controller, a battery bank, an inverter, and a refrigeration load was then defined to guide the design process.

The cooling load on the cold room was determined analytically by separately calculating the transmission, infiltration, product, occupant, lighting, and fan motor loads, the sum of which constitutes the total refrigeration demand for the facility. This cooling load, together with the solar PV sizing relations and the design constraint of at least 48 hours of autonomous operation without solar input, was used to size the required PV array, battery bank, and inverter capacities.

Finally, an economic evaluation framework based on the Simple Payback Period and Net Present Value was adopted to compare the proposed locally fabricated design against an imported equivalent system. Together, these methods provide the technical and economic basis for the results presented and discussed in Chapter 4.

Chapter 4

Results and Discussion

4.1 Cooling Load Calculation Results

The total cooling load calculation consists of several components, namely product load, transmission load, load from human activities, air infiltration load, and equipment load. The results of the cooling load calculations for the cold room are presented in Table 4.1.

Table 4.1: Cooling Load Calculation Results in the Cold Storage.

$q_{transmission}$ (kW)	$q_{infiltration}$ (kW)	$q_{product}$ (kW)	$q_{occupants}$ (kW)	$q_{lighting}$ (kW)	q_{fan} (kW)	total (kW)
0.134	3.68	40.55	0.127	0.033	0.571	45.1

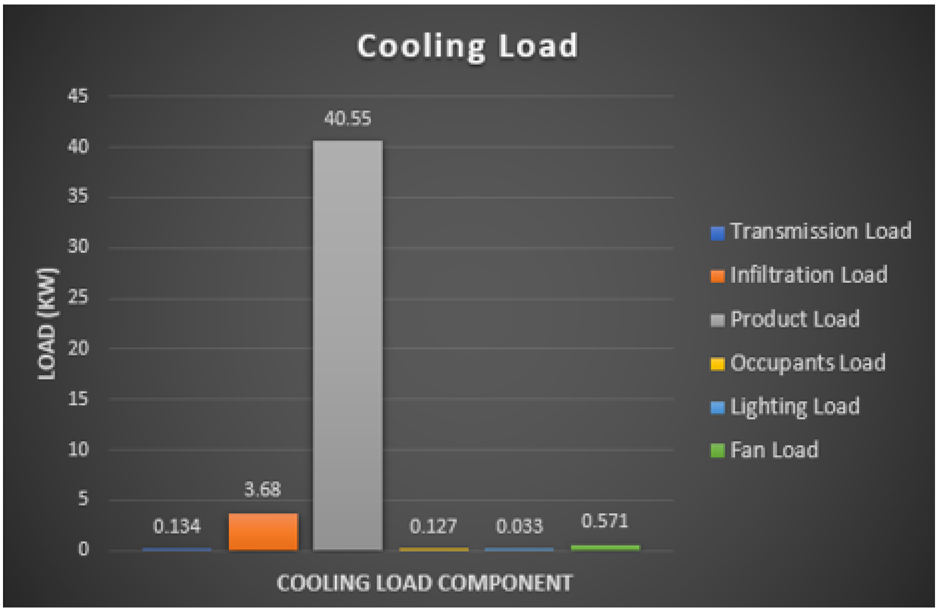

Figure 4.1: Cooling Load Graph.

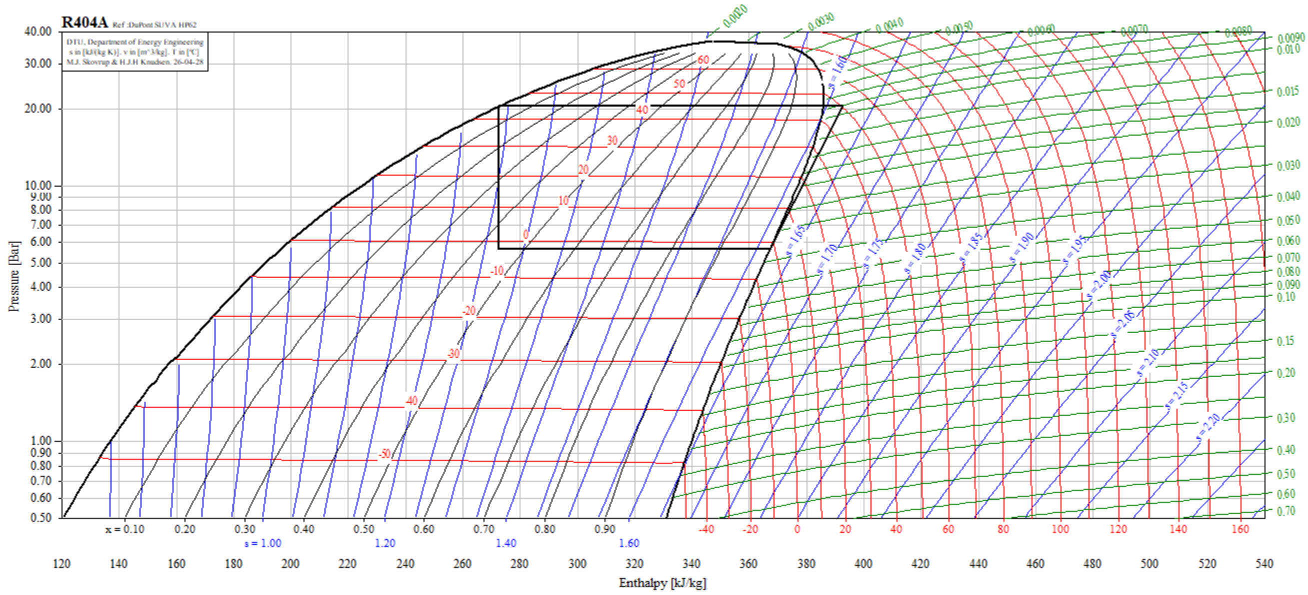

Figure 4.2: P-h Diagram for R-404A.

The Figure 4.1 is a graph that indicates good insulation of the cold room since the system supplies to meet the product load mostly rather than unnecessary loads.

4.2 Refrigeration Unit Selection

In the design of the cold storage refrigeration system, the cooling load calculation is carried out carefully by considering divers loads, along with the application of a 10% safety factor in accordance with the guidelines outlined in the Cooling and Heating Load Calculation Manual. This factor is intended to anticipate unforeseen conditions and ensure that the system remains capable of operating optimally under varying circumstances.

The determination of temperature parameters is one of the critical aspects. The final product temperature is set at 5°C while the evaporator temperature is set at -2°C maintaining a minimum temperature difference of 7°C from the cold storage room to ensure efficient heat exchange. Meanwhile, the condenser temperature is set at 45°C, adjusted to the ambient air temperature of approximately 35°C to support the performance of the air-cooled condenser type.

The refrigerant used in this system is R-404A, in accordance with the recommendations provided in the TP ATP Handbook 2021 (Committee, 2022). Based on the available temperature and pressure data, the refrigeration cycle is analyzed and visualized using a pressure-enthalpy (p-h) diagram generated with CoolPack software to obtain the enthalpy values at each point in the process. h1, h2 and h3 values were obtained from the enthalpy diagram which are vital in refrigerationn equipment sizing see 4.2

The selection of the main refrigeration components presented in Table 4.2 was based on a rigorous

Table 4.2: Specifications of the Designed Refrigeration

‘ **Specification**	**Evaporator**	**Condenser**	**Compressor**	**Lighting**	**Fan**	**Total**
Model	GHN 080.3D/24-AHS50.M	GVW 080.2/2-N(S).M	4CES-6Y-40S	two-40W LED	YWF Series Axial	
Cooling Capacity (kW)	7.06	38.8	10.5			**56.36(kW)**
Operating Temperature (°C)	5	45	70	50	60	
Refrigerant	R-404A	R-404A	R-404A			
Power Consumption (kW)	0.75	0.75	7.5	0.6	2.854	**12.454(kW)**
Voltage (V)	240	240	240	240	240	**240V**
Current (A)	3.125	3.125	31.25	2.5	11.875	**51.875A**

sizing process and the need to ensure compatibility with the system's thermal and operational requirements.

4.3 Solar Power System Modeling with HOMER Pro

To model the solar power system at Bwondha Fish landing Site location using HOMER Pro, the first step was to input the solar radiation and daily temperature data obtained from NASA POWER. The monthly solar radiation data indicates average daily values that range from 4.24 kWh/m²/day in January to 5.5 kWh/m²/day in September (see Figure 4.3).

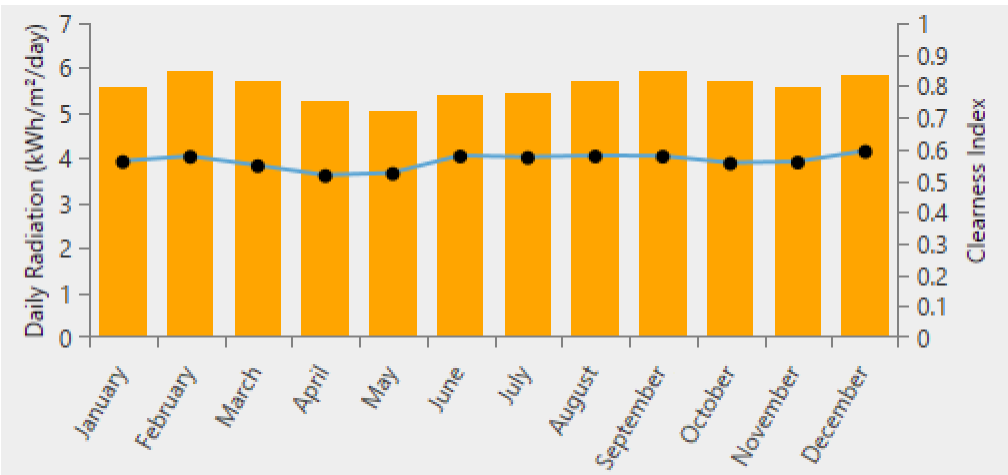

Figure 4.3: Monthly Average Solar Global Horizontal Irradiance (GHI).

Next, the solar power system is configured in HOMER Pro by incorporating components such as solar panels, inverters, and batteries. The system is also connected to the local power grid to ensure a stable energy supply.

In this design system utilizing HOMER Pro, electrical energy is generated by the Fron3.1 monocrystaline solar panels, which convert sunlight into DC energy. This energy is then converted into AC electricity by the Leon5 inverter, which is distributed to meet the electric load demand of 12.5 kW. Excess energy is stored in sonnEco12-Lithium batteries, allowing it to be used when sunlight is unavailable. For a detailed schematic of the system architecture, see Figure 4.4.

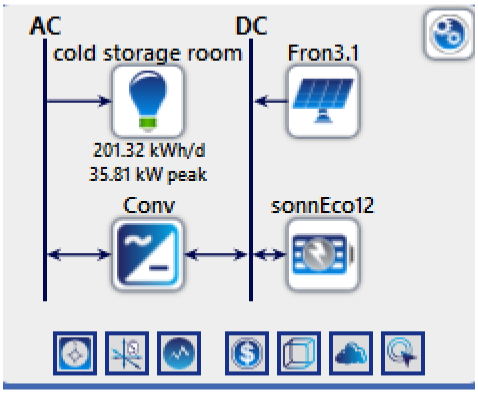

Figure 4.4: PV Hybrid Schematic with HOMER Pro.

4.4 Electrical Load

HOMER Pro is used to design a renewable energy generation system with a specific capacity. The Daily Profile graph illustrates the daily energy consumption pattern in kilowatts (kW), with the X-axis representing the hours of the day and the Y-axis showing the power used. Power consumption peaks at around 9:00 AM, and decreases after 6:00 PM. Power consumption remains stable between 9:00 AM and 3:00 PM, reflecting a scheduled peak load, before declining during the evening hours. For a visual representation of this load profile, see Figure 4.5.

In this system, the total desired capacity to meet the energy demand was established at 12.5 kW, which corresponds to the total power consumption required by the cold storage facility and comparable applications. The selected solar panel type, offers a capacity of 240 Wp per module. To achieve the target capacity, the system utilizes multiple panels arranged in series and parallel configurations to satisfy the necessary power requirements. This design decision was shaped by practical considerations, particularly the limited surface area available on the 20-foot reefer container structure, which inherently constrains the maximum deployable PV capacity.

Figure 4.6 illustrates the power output profile of the photovoltaic system over the course of one year. The heatmap visualization highlights the variation in output, with warmer colors indicating periods of higher generation and cooler colors reflecting lower or zero production during non-sunny intervals.

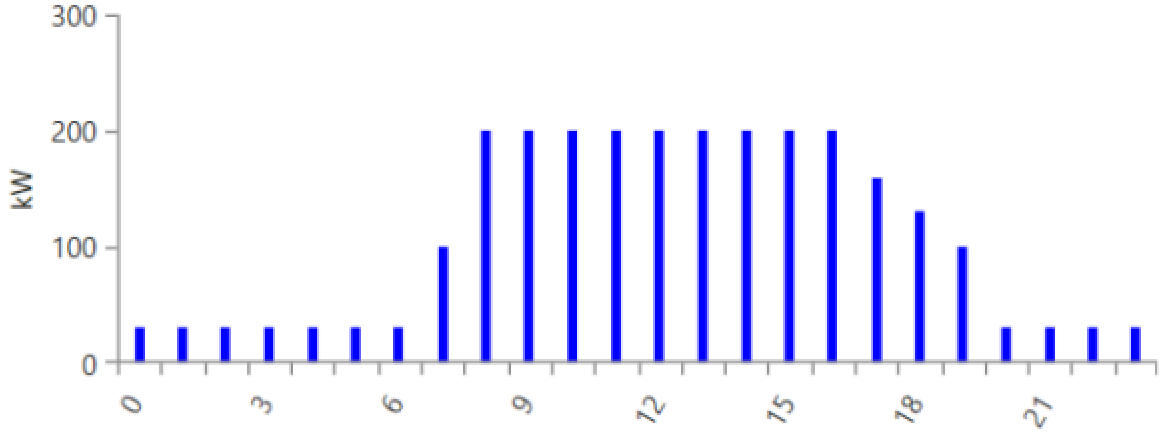

Figure 4.5: Daily Profile Graph of Electrical Power Consumption.

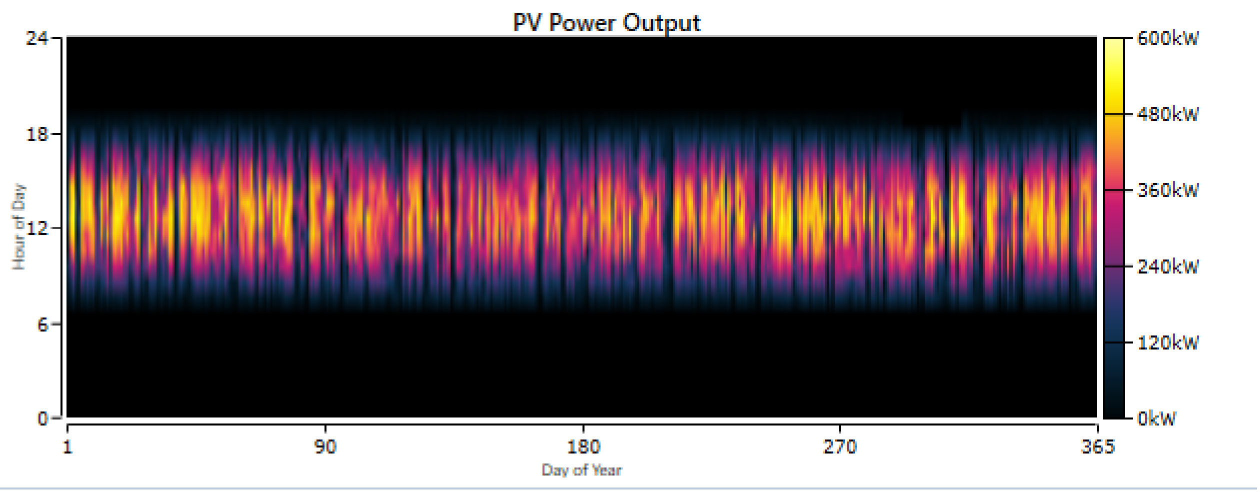

Figure 4.6: PV Power Output Graph.

According to the simulation results, the system achieves an average output of 2.49 kW, or approximately 108 kWh per day, translating to a capacity factor of 18.3%. Under optimal conditions, the PV array can reach a peak output of 14.9 kW, while the minimum output falls to 0 kW during extended periods of low irradiance. Cumulatively, the PV system generates 21,812 kWh annually and operates for 4,380 hours each year (see Table 4.3).

4.4.1 Battery Selection

The selection of the Hitachi SonnEco12 lithium-ion battery was informed by both technical performance considerations and simulation data obtained in HOMER Pro. This battery model was chosen due to its proven ability to sustain a consistently high state of charge (SOC) under the specific load profile of the cold storage system. As illustrated in Figure 4.7, the heatmap shows that the SOC ranged between approximately 60% and 100% throughout the year, with the majority of operational hours maintaining levels above 95%. The monthly boxplot further confirms this stability, demonstrating an

Table 4.3: Photovoltaic System Performance Summary

Parameter	Value	Units
Rated Capacity	15.5	kW
Mean Output (Power)	2.49	kW
Mean Output (Energy)	59.76	kWh/day
Capacity Factor	16.3	%
Total Production	21,812	kWh/year
Minimum Output	0	kW
Maximum Output	14.9	kW
PV Penetration	4.44	%
Hours of Operation	4,380	hours/year
Levelized Cost of Energy	3.00	Rp/kWh

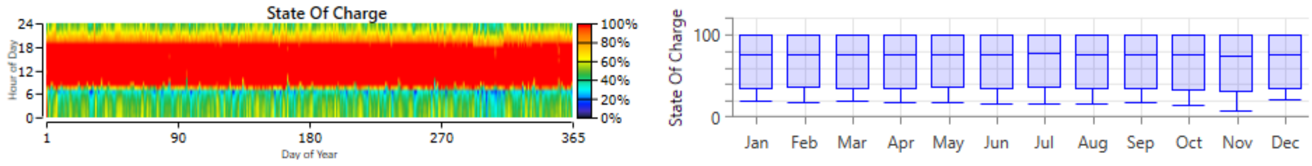

Figure 4.7: Battery State of Charge Graph.

average SOC close to 100% and minimal variability across different months. These results indicate that the SonnEco12 battery effectively mitigates the intermittency of solar generation while providing reliable energy storage capacity to support refrigeration loads. Additionally, this battery is commercially available in the market, offers high cycle life and efficiency, and integrates seamlessly into the hybrid PV-battery configuration modeled in this study. Collectively, these characteristics ensured that the SonnEco12 was a technically robust and economically appropriate choice for the application.

4.4.2 Inverter Selection

The Leonics S-219Cp inverter was selected for this design due to its combination of high efficiency, modular expandability, and compatibility with hybrid photovoltaic systems. This inverter provides a certified conversion efficiency of 96%, which is essential for reducing energy losses during the conversion from direct current (DC) generated by the PV array to alternating current (AC) used by the refrigeration equipment. Each unit is rated at 6 kW, and the system design incorporates two inverters connected in parallel to achieve the total capacity requirement of 18 kW. The inverter supports parallel configuration of up to ten units, offering flexibility for future expansion or capacity adjustments without requiring substantial changes to the system architecture. Furthermore, the model has a documented operational lifespan of approximately ten years, which supports the long-term reliability of the cold storage installation. The S-219Cp is also widely available in markets. These factors collectively made this inverter a technically sound and practically appropriate choice for integration into the hybrid PV-battery configuration.

4.5 Cold Room Design

4.5.1 Materials, Capacity and Dimensions

The main structure of the facility is built using polyurethane (PUF) insulated panels, 100 mm thick, which form the door, walls, and roof, providing effective thermal insulation throughout. The floor is constructed from a concrete slab combined with extruded polystyrene (XPS) insulation, ensuring durability while minimizing heat transfer from below.

To maintain an airtight seal and prevent insulation losses, silicone sealants and gaskets are used throughout the structure. Mechanical strength and structural integrity are provided by stainless steel components along with fasteners such as bolts, nuts, and screws. Finally, aluminum panels were used for the inner shelves, offering a lightweight yet sturdy solution for internal storage.

The site has a daily catch of 1.7 tonnes of fish. Of this total, 40% remains unsold each day, amounting to 0.68 tonnes of fish that must be placed into storage daily.

Since unsold fish needs to be stored for up to 5 days before it spoils, the total storage capacity required is calculated by multiplying the daily stored amount by the number of storage days: 0.68 tonnes × 5 days, giving a total storage capacity requirement of 3.4 tonnes. To accommodate this volume, 34 crates are needed, each with a capacity of 100 kg, together providing the necessary 3.4 tonnes of storage.

The storage room itself measures 5 m × 2 m × 3 m, providing sufficient space to house the required crates and meet the facility's cold storage needs. This was designed in coolselector2 software see Figure 4.8.

4.5.2 List of Materials

The selected materials for the design of the cold storage room are indicated in the Table 4.4

4.6 Testing of Results

Figure 4.9 shows the MATLAB/Simulink model developed to simulate the performance of the proposed solar-powered cold room system. The simulation model consists of a photovoltaic (PV) array, Maximum Power Point Tracking (MPPT) controller, DC–DC converter, battery storage system, inverter, and load components. The PV array converts solar energy into electrical power, while the

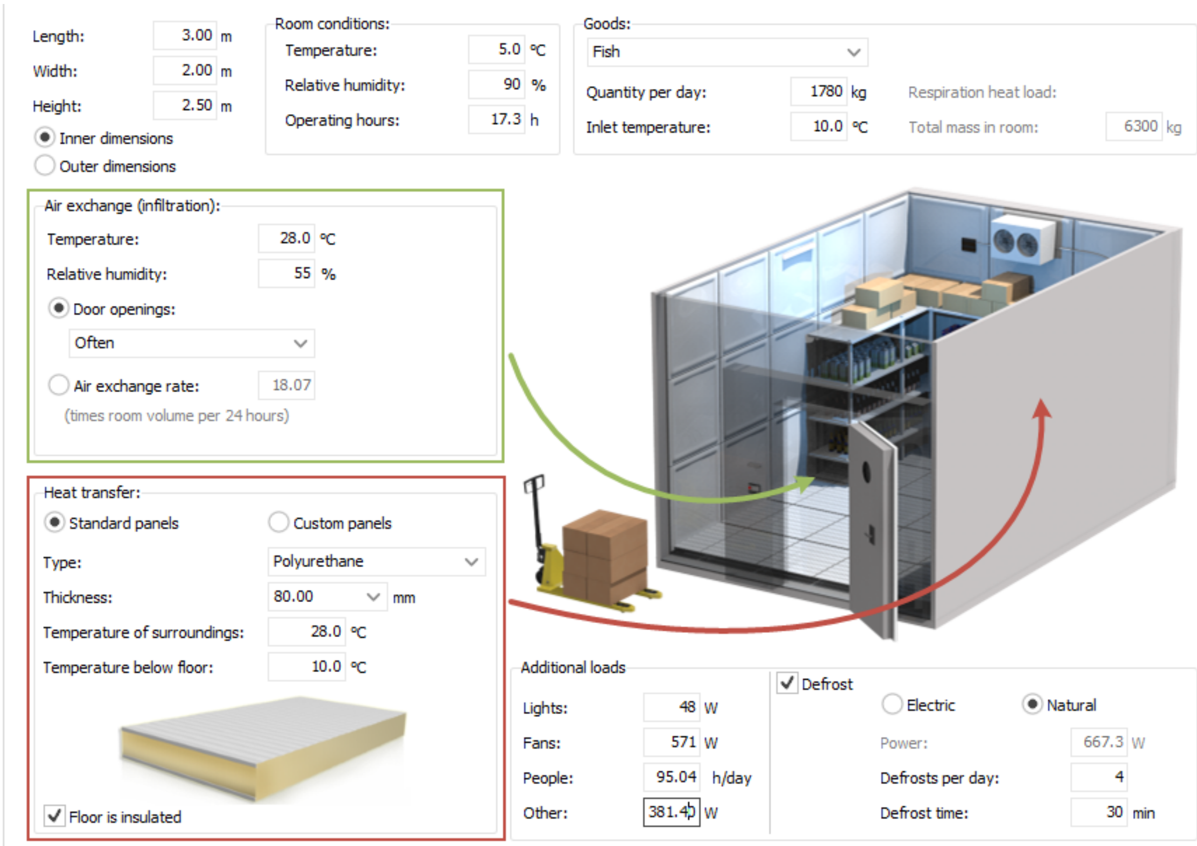

Figure 4.8: Cold Room as Designed in Coolselector2 Software.

MPPT algorithm continuously adjusts the operating point of the PV modules to extract maximum available power under varying solar irradiance conditions.

The generated DC power is processed through a DC–DC converter and used to charge the battery bank as well as supply the system load. The battery serves as an energy storage unit, ensuring uninterrupted operation during periods of low solar generation. The inverter converts the stored DC energy into AC power suitable for operating the refrigeration equipment and auxiliary loads of the cold room.

The simulation also incorporates voltage, current, and power measurement blocks to monitor system performance in real time. The waveform displayed on the right-hand side represents the AC output voltage generated by the inverter, demonstrating stable sinusoidal operation. Through this simulation, the electrical behavior of the solar power system was analyzed, verified, and optimized before practical implementation, ensuring reliable and efficient operation of the solar-powered cold storage facility.

4.7 Economic Analysis and Design Alternatives

An economic comparison was conducted between the proposed locally designed solar powered cold room system (Option A) and an imported equivalent system from China (Option B). The comparison considered key financial indicators including capital cost, operation and maintenance (O & M)

Table 4.4: List of Materials

Category	Material/Component	Purpose
Structure	Galvanized steel frame	Supports cold room structure
Wall & Roof Insulation	PUF sandwich panels (100–150 mm)	Minimizes heat gain
Floor System	Concrete slab with XPS insulation	Supports load and reduces heat transfer
Door Assembly	Insulated cold room door with rubber gaskets	Provides airtight access
Refrigeration Unit	Compressor (4CES-6Y-40S)	Compresses refrigerant
Refrigeration Unit	Evaporator (GHN 080.3D/24-AHS50.M)	Absorbs heat from cold room
Refrigeration Unit	Evaporator (GHN 080.3D/24-AHS50.M)	Absorbs heat from cold room
Refrigerant	R-404A	Cooling medium
Piping	Copper refrigerant pipes	Refrigerant circulation
Electrical System	LED lighting	Interior illumination
Electrical System	Temperature controller & sensors	Temperature monitoring and control
Solar PV System	26 × 600 W solar panels	Generates electrical power
Solar PV System	MPPT charge controller	Optimizes battery charging
Solar PV System	7 × 48 V, 500 Ah batteries	Energy storage
Solar PV System	3 × 15 kW inverters	Converts DC to AC power
Safety & Accessories	Circuit breakers, earthing system, fire extinguisher	System protection and safety

cost, payback period, and net present value (NPV). The results indicate that the local design option requires a total capital investment of UGX 1,404,655,750 (approximately USD 371,600), which is significantly lower than the UGX 1,800,000,000 (approximately USD 486,500) required for the imported alternative. This represents a cost saving of UGX 395,344,250, equivalent to approximately 22% reduction in initial investment cost.

In terms of operating expenses, the local design also demonstrates superior performance, with an annual operation and maintenance cost of UGX 35,116,394 compared to UGX 45,000,000 for the imported system. This results in annual savings of UGX 9,883,606, reducing the long-term operational burden on the facility owner.

The financial viability assessment further shows that the locally designed system achieves a simple payback period of 3.2 years, compared to 4.1 years for the imported alternative. This means that the local design recovers its investment approximately 0.9 years faster, making it a more attractive

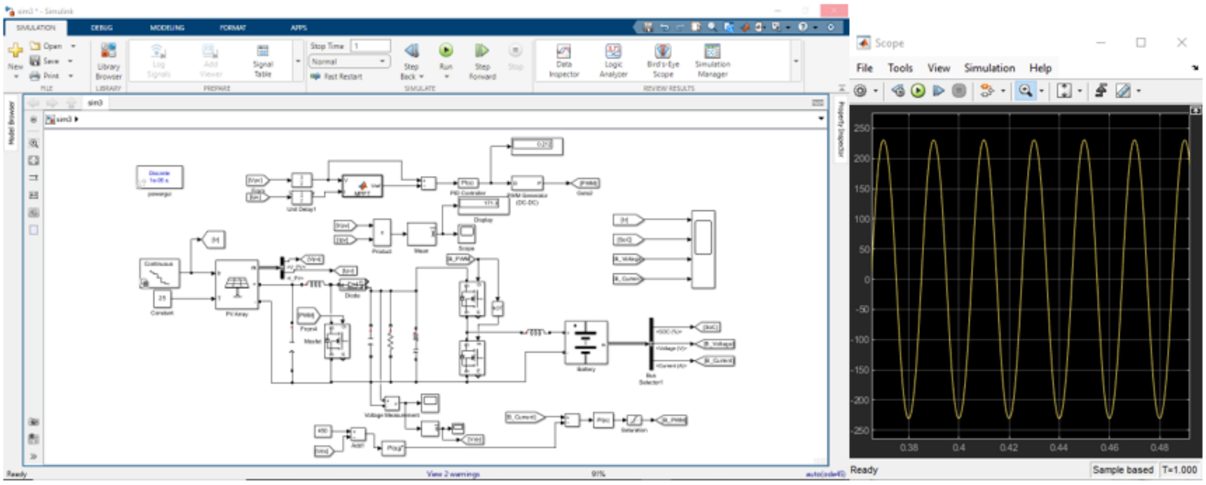

Figure 4.9: System Simulation in Simulink.

investment option.

Additionally, the 20-year Net Present Value (NPV) analysis reveals that the local design generates a value of UGX 1,841,200,000, while the imported option yields UGX 1,446,400,000. The local system therefore provides an additional UGX 394,800,000 in economic benefit over the project lifetime.

Based on the comparative analysis, Option A (Local Design) is the preferred alternative due to its lower capital cost, reduced maintenance expenses, shorter payback period, and higher long-term economic returns. Beyond the financial advantages, the local design promotes local manufacturing, simplifies maintenance through easier access to spare parts and technical expertise, and contributes to national capacity building in renewable energy and cold-chain technologies. see Table 4.5

Reasons the local design is cheaper:

1. Uses locally available materials.
2. Lower labor and installation costs.
3. No import duties, shipping, or customs charges.
4. Easier and cheaper maintenance.
5. Locally available spare parts.
6. Optimized for actual site requirements, reducing oversizing.
7. Lower long-term operating costs.

Table 4.5: Economic Comparison Between Local Design and Imported Cold Room System

Parameter	**Option A: Local Design**	**Option B: Import (China)**	**Difference**
Total Capital Cost (UGX)	UGX 1,404,655,750	UGX 1,800,000,000	–UGX 395,344,250
Total Capital Cost (USD)	≈ USD 371,600	≈ USD 486,500	–USD 114,900
Saving vs Import Option	22% cheaper than import	Baseline	
Annual O&M Cost (UGX)	UGX 35,116,394	UGX 45,000,000	–UGX 9,883,606
Simple Payback vs Diesel (yrs)	3.2 years	4.1 years	0.9 years faster
20-year NPV vs Diesel (UGX)	UGX 1,841,200,000	UGX 1,446,400,000	+UGX 394,800,000
Recommended Option	**Option A – Local Design**		

4.8 Performance Analysis Design Options

A technical performance comparison was conducted between the proposed locally designed solar-powered cold room system (Option A) and an equivalent imported cold room system (Option B). The comparison focused on cooling capacity, electrical power consumption, coefficient of performance (COP), storage capacity, battery autonomy, and operational reliability. The coefficient of performance (COP) was determined using Equation 4.1.

$$COP = \frac{\text{Cooling Capacity}}{\text{Electrical Power Input}}. \tag{4.1}$$

For the locally designed system,

$$COP_{local} = \frac{56.36}{12.454} = 4.53 \tag{4.2}$$

For the imported system [3],

$$COP_{imported} = 4.41 \tag{4.3}$$

The percentage improvement in COP of the local design relative to the imported system is given by

$$\%\ \text{Difference} = \frac{COP_{local} - COP_{imported}}{COP_{imported}} \times 100, \tag{4.4}$$

Table 4.6: Performance Comparison Between Local Design and Imported System

Parameter	**Option A: Local Design**	**Option B: Imported System**	**Difference**
Cooling Capacity (kW)	56.36	55.80	+0.56
Electrical Power Consumption (kW)	12.454	12.65	-0.196
Coefficient of Performance (COP)	4.53	4.41	+2.7%
Storage Capacity (tonnes)	3.4	3.4	0
Battery Autonomy (hours)	48	48	0
PV Capacity (kWp)	15.5	15.5	0
Temperature Range (°C)	-5 to 5	-5 to 5	0
Reliability (%)	98.6	98.0	+0.6

$$= \frac{4.53 - 4.41}{4.41} \times 100 = 2.7\% \tag{4.5}$$

The performance comparison results presented in Table 4.6 indicate that both systems provide nearly identical refrigeration performance. The locally designed system achieves a cooling capacity of 56.36 kW while consuming 12.454 kW of electrical power, resulting in a COP of 4.53. The imported system achieves a COP of 4.41 under similar operating conditions. The difference of only 2.7% demonstrates that both systems exhibit comparable refrigeration efficiency.

Furthermore, both alternatives provide the same storage capacity of 3.4 tonnes, battery autonomy of 48 hours, photovoltaic capacity of 15.5 kWp, and operating temperature range of -5°C to 5°C. This confirms that both systems satisfy the cooling requirements for fish preservation.

Although the imported system provides similar refrigeration performance, the locally designed system exhibits a slightly higher COP and reliability due to optimization for local climatic conditions and operational requirements. The improved efficiency translates into lower energy consumption and reduced operating costs over the system lifetime.

Therefore, while both alternatives achieve comparable technical performance, the locally designed solar-powered cold room is preferred because it combines equivalent cooling effectiveness with superior economic benefits and lower lifecycle costs.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

This study assessed and designed a solar-powered cold storage system intended to reduce post-harvest fish losses and improve the incomes of small-scale fishers at Bwondha Landing Site, Uganda. The following conclusions are drawn:

1. Site assessment confirmed Bwondha as a high-potential site for intervention: it hosts roughly 200 fishermen and 58 boats, lands an average of 1.7 tonnes of fish daily, and currently has no functional cold storage, relying instead on smoking and sun-drying methods that reduce fish quality and market value.

2. Cooling load analysis showed a total cold room cooling load of 45.1 kW, with the product load (40.55 kW) accounting for the vast majority of this demand, while transmission, infiltration, occupant, lighting, and fan loads remained comparatively small — indicating an efficiently insulated cold room envelope.

3. Refrigeration system design, based on R-404A refrigerant, produced an evaporator–condenser˘ compressor combination with a total cooling capacity of 56.36 kW and a total electrical power consumption of 12.454 kW, providing adequate capacity (including the applied 10% safety factor) to meet the calculated cooling load.

4. Solar PV and storage sizing, modeled in HOMER Pro using NASA POWER irradiance data for Bwondha (4.24–5.5 kWh/m^2/day), resulted in a 15.5 kWp PV array paired with a 48 V, 3500 Ah lithium-ion battery bank (SonnEco12) and Leonics S-219Cp inverters (96% efficiency). Simulation results showed the battery state of charge remaining above 95% for most of the year, demonstrating that the hybrid system can reliably meet the 12.5 kW electrical load even during periods of low solar irradiance.

5. Cold room design, carried out in CoolSelector2, produced a 5 m × 2 m × 3 m insulated room (100 mm PUF panels) with capacity for 3.4 tonnes of fish — sufficient to store the approximately 0.68 tonnes of unsold catch accumulated daily over a 5-day holding period.

6. System validation via MATLAB/Simulink confirmed stable electrical behavior across the PV-battery-inverter-refrigeration chain, with the inverter producing a clean sinusoidal AC output, supporting the feasibility of the design prior to physical implementation.

7. Economic analysis showed that the locally fabricated design (Option A) outperforms an imported Chinese equivalent (Option B) on every financial metric assessed: approximately 22% lower capital cost (UGX 1.40 billion vs. UGX 1.8 billion), lower annual operation and maintenance costs (UGX 35.1 million vs. UGX 45 million), a shorter payback period (3.2 years vs. 4.1 years), and a higher 20-year Net Present Value (UGX 1.84 billion vs. UGX 1.45 billion).

8. Performance Analysis revealed that the locally designed solar-powered cold room achieved a COP of 4.53, which is slightly higher than the COP of 4.41 obtained for the imported system. The difference of 2.7% indicates that both systems provide nearly identical refrigeration performance. Furthermore, both alternatives offer the same storage capacity, photovoltaic generation capacity, battery autonomy, and temperature control capabilities required for fish preservation. Therefore, the locally designed system satisfies all technical performance requirements while matching the operational effectiveness of the imported alternative. The results confirm that local fabrication can provide refrigeration performance comparable to imported systems without compromising cooling efficiency or reliability.

Taken together, these findings filled in the research gaps of: Insufficient local operating data, Economic feasibility not fully established and Comparative studies being few, the findings also confirm that a solar-powered cold storage system is both technically feasible and economically viable for small-scale fisheries at Bwondha. It offers a sustainable, off-grid alternative to diesel-based refrigeration and traditional preservation methods, while also proving more cost-effective than imported Turkey or China alternatives — supporting the case for local design and fabrication of solar cold chain infrastructure in Uganda's fisheries sector.

5.2 Recommendations

Based on the findings of this study, the following recommendations are made:

1. Pilot implementation: The designed system should be implemented as a pilot installation at Bwondha Landing Site to validate field performance against the HOMER Pro and Simulink simulation results, and to gather real operational data under tropical lakeside conditions.

2. Capacity building: Local fishermen, traders, and technicians should be trained in the operation and basic maintenance of the PV-battery-refrigeration system. A cooperative ownership and

management model, as identified in the literature review, is recommended to improve affordability and long-term sustainability.

3. Financing and partnerships: Government agencies, NGOs, and financial institutions should be engaged to provide subsidies, grants, or microfinance schemes that address the high upfront capital cost, which remains the principal barrier to adoption of solar cold storage in small-scale fisheries.

4. Remote monitoring: Future installations should incorporate IoT-based sensors for real-time tracking of temperature, battery state of charge, and system performance, enabling predictive maintenance and reducing the risk of unplanned downtime.

5. Local manufacturing and supply chains: Given the demonstrated cost advantage of the local design, investment in local fabrication capacity and spare-parts supply chains should be prioritized over reliance on imported systems.

6. Detailed engineering review: Prior to procurement and installation, a detailed engineering design review is recommended to confirm full compatibility between the calculated cooling load, the selected refrigeration equipment, and the sized PV-battery-inverter system, ensuring all components are matched with consistent design margins.

7. Further research: Future work should explore the integration of Phase Change Material thermal storage to reduce battery sizing and cost, conduct a full life-cycle cost analysis, and evaluate system performance across seasonal variations in solar irradiance and catch volume.

8. Scaling and replication: Once validated at Bwondha, the design should be replicated at other landing sites with similar catch volumes and off-grid conditions along Lake Victoria and other major water bodies in Uganda, contributing to broader reduction of post-harvest losses in the national fisheries sector.

References

[1] Food and Agriculture Organization (FAO), "Reducing post-harvest losses in fisheries through cold chain development," Food and Agriculture Organization of the United Nations, Tech. Rep., 2021. [Online]. Available: https://www.fao.org/3/cd5864en/online/cd5864en.html

[2] S. Nabwire, "Solar-powered fish preservation systems for east africa," *Renewable Energy Journal*, vol. 18, no. 4, pp. 112–124, 2022.

[3] International Renewable Energy Agency (IRENA), "Solar cooling technologies: Market and policy outlook," IRENA, Tech. Rep., 2023. [Online]. Available: https://www.irena.org/publications

[4] Ministry of Energy and Mineral Development (Uganda), "Uganda renewable energy policy framework," Ministry of Energy and Mineral Development, Uganda, Tech. Rep., 2021. [Online]. Available: https://s3-eu-west-1.amazonaws.com/s3.sourceafrica.net/documents/118159/Uganda-Renewable-Energy-Policy.pdf

[5] J. Okello, D. Lwanga, and F. Mukasa, "Community-based solar cold chain financing for small-scale fisheries," *Journal of Renewable Energy Systems*, vol. 12, no. 1, pp. 33–48, 2023.

[6] A. Oyelami, "Photovoltaic cold storage for perishable goods in sub-saharan africa," *Energy for Sustainable Development*, vol. 57, pp. 95–103, 2020.

[7] D. Musinguzi, R. Nanyonga, and P. Namaganda, "Renewable energy adoption for rural fisheries in uganda," *Journal of Sustainable Energy Studies*, vol. 15, no. 2, pp. 45–58, 2022.

[8] United Nations Environment Programme (UNEP), "Sustainable energy solutions for rural value chains in africa," UNEP, Tech. Rep., 2020. [Online]. Available: https://projects.unep.org/docs/gef/documents/PIRs/2020/1609/Project%20Documents/1609_Project_AppraisalDocument_CEO%20Endorsement_Rev.pdf

[9] L. Kitinoja, V. Tokala, and M. Mohammed, "Clean cold chain development and the critical role of extension education," *Agriculture Development*, 2019.

[10] H. H. Pourasl *et al.*, “Solar energy status in the world: A comprehensive review,” *Energy Reports*, vol. 9, pp. 1–20, 2023.

[11] T. Z. Ang *et al.*, “A comprehensive study of renewable energy sources: Classifications, challenges and suggestions,” *Energy Strategy Reviews*, vol. 43, 2022.

[12] C. de Castro *et al.*, “Global solar electric potential: A review of the technical and sustainable limits,” *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 824–835, 2013, updated contexts in recent assessments.

[13] M. A. Raza *et al.*, “Global solar energy potential forecasting through machine learning and deep learning models,” *Scientific Reports*, vol. 16, 2026.

[14] A. O. Ali *et al.*, “Advancements in photovoltaic technology: A comprehensive review of recent advances and future prospects,” *Energy Conversion and Management: X*, vol. 26, 2025.

[15] Z. Ma *et al.*, “Advances and development trends in solar photovoltaic-thermal technology: a review,” *Clean Energy*, vol. 9, no. 4, pp. 98–122, 2025.

[16] International Renewable Energy Agency (IRENA), “Renewable capacity statistics 2024,” International Renewable Energy Agency, Tech. Rep., 2024. [Online]. Available: https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024

[17] T. Ibrahim *et al.*, “A comprehensive review of solar energy systems: Technical, economic, and environmental perspectives for sustainable development,” *International Journal of Thermal Sciences*, 2025, in press or forthcoming; volume/issue pending.

[18] Various authors, “Various pv/t and bipv reviews, e.g., in solar energy journal updates,” 2024–2025, composite reference for photovoltaic-thermal and building-integrated photovoltaics literature in Solar Energy journal.

[19] International Energy Agency (IEA), *World Energy Outlook 2024*. Paris: International Energy Agency, 2024. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2024

[20] S. T. Gebreabe *et al.*, “Advances in solar energy technologies: A comprehensive review of photovoltaic, thermal, and hybrid systems,” 2025, preprint, conference paper, or journal article forthcoming.

[21] SolarPower Europe, “Global market outlook for solar power 2025-2029,” SolarPower Europe, Tech. Rep., 2025. [Online]. Available: https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2025-2029

[22] T. S. Kishore *et al.*, “Review of global sustainable solar energy policies,” *Sustainable Energy Technologies and Assessments*, 2025, volume/issue pending.

[23] Our World in Data and International Renewable Energy Agency (IRENA), "Our world in data / irena datasets, 2023–2025 updates," Online datasets and visualizations, 2023–2025. [Online]. Available: https://ourworldindata.org/renewable-energy

[24] A. G. Olabi *et al.*, "Renewable energy systems: Comparisons, challenges and barriers," *Cleaner Engineering and Technology*, 2023.

[25] Q. Hassan *et al.*, "A review of hybrid renewable energy systems: Solar and wind-powered solutions," *Results in Engineering*, 2023.

[26] International Energy Agency and International Renewable Energy Agency and others, "Projections from iea, irena, and recent forecasting studies," 2024–2026, composite reference for solar energy deployment and capacity projections.

[27] K. R. Ngoy *et al.*, "Lithium-ion batteries and the future of sustainable energy: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 223, Nov 2025.

[28] M. M. Hasan *et al.*, "Advancing energy storage: The future trajectory of lithium-ion battery technologies," *Journal of Energy Storage*, vol. 120, Jun 2025.

[29] BloombergNEF, "Lithium-ion battery pack prices fall to $108/kwh; stationary storage becomes lowest-price segment," Online report, 2025, referenced in ESS News, December 2025. [Online]. Available: https://about.bnef.com/blog/lithium-ion-battery-pack-prices-fall-to-108-kwh-stationary-storage-becomes-lowest-price-segment/

[30] Ember, "Storing solar electricity using utility-scale batteries has dropped to just $65/mwh," Online report / analysis, 2025. [Online]. Available: https://ember-energy.org/insights/storing-solar-electricity-using-utility-scale-batteries/

[31] International Energy Agency, *Electricity 2026*. Paris: International Energy Agency (IEA), 2026. [Online]. Available: https://www.iea.org/reports/electricity-2026

[32] IDTechEx, "Batteries for stationary energy storage 2025-2035: Markets, forecasts, players, and technologies," IDTechEx, Market report, 2025. [Online]. Available: https://www.idtechex.com/en/research-report/batteries-for-stationary-energy-storage-2025-2035/

[33] P. Parvizi *et al.*, "From present innovations to future potential: The promising journey of lithium-ion batteries," *Micromachines*, vol. 16, no. 2, 2025.

[34] H. Yang, "Advances in battery technologies for smart grids in 2025," *Nature Reviews Electrical Engineering*, 2026, year in Review.

[35] W. Li *et al.*, "Advanced batteries for sustainable energy storage," *Green Energy & Environment*, vol. 10, no. 11, pp. 2201–2258, Nov 2025.

[36] Various authors, “Various reviews in batteries (mdpi),” Aug 2025, special issue / collection of reviews on battery technologies.

[37] S. Tibude *et al.*, “Hybrid energy storage system: A review of strategies and applications,” *IEEE Access*, 2024, iEEE publication.

[38] A. Ravi *et al.*, “Energy storage systems - energizing the future: A review,” *E3S Web of Conferences*, vol. 611, 2025.

[39] BloombergNEF, “Global energy storage market outlook 2h 2025,” Market outlook report, 2025. [Online]. Available: https://about.bnef.com/blog/global-energy-storage-market-outlook-2h-2025/

[40] T. Jaradat *et al.*, “A review of battery energy storage system for renewable energy penetration,” *Future Batteries*, vol. 7, Sep 2025.

[41] International Energy Agency, “Global battery markets are growing strongly – and so are the supply risks,” IEA commentary / report, Feb 2026. [Online]. Available: https://www.iea.org/commentaries/global-battery-markets-are-growing-strongly-and-so-are-the-supply-risks

[42] N. Bhandari *et al.*, “Advancements in lithium-ion batteries: sustainability and market impact,” 2025, conference paper, report, or preprint.

[43] U.S. Department of Energy, “Battery energy storage systems report,” U.S. Department of Energy, Tech. Rep., Nov 2024, updated contexts 2025. [Online]. Available: https://www.energy.gov/oe/battery-energy-storage-systems-report

[44] L. Xie *et al.*, “Review of lithium-ion battery energy storage systems,” 2024, iEEE publication.

[45] BloombergNEF and International Energy Agency and IDTechEx, “Projections from bnef, iea, and idtechex reports,” 2025–2026, composite reference for long-term battery storage capacity and market projections.

[46] H. Takeshima *et al.*, “Solar-powered cold-storages and sustainable food system transformation: Evidence from horticulture markets interventions in northeast nigeria,” International Food Policy Research Institute (IFPRI), Discussion Paper, 2021, iFPRI Discussion Paper. [Online]. Available: https://www.ifpri.org/publication/solar-powered-cold-storages-and-sustainable-food-system-transformation-evidence-horticulture

[47] W. Amjad, A. Munir, F. Akram, A. Parmar, M. Precoppe *et al.*, “Decentralized solar-powered cooling systems for fresh fruit and vegetables to reduce post-harvest losses in developing regions: a review,” *Clean Energy*, vol. 7, no. 3, pp. 635–653, 2023.

[48] K. Shah and H. Bhargav, “A review on solar powered cold storage integrated with thermal energy storage,” *International Journal of Novel Research and Development*, vol. 8, no. 5, 2023, available at: https://ijnrd.org/viewpaperforall.php?paper=IJNRD2305493.

[49] A. Sinha and S. R. Karale, “A review on solar powered refrigeration and the various cooling thermal energy storage (ctes) systems,” *International Journal of Engineering Research & Technology*, vol. 2, no. 2, 2013, updated contexts from later reviews. [Online]. Available: https://www.ijert.org/research/a-review-on-solar-powered-refrigeration-and-the-various-cooling-thermal-energy-storage-ctes-systems-IJI pdf

[50] Various authors, “Various sources including pcm integration studies (e.g., guo et al., 2025; natarajan et al., 2023),” 2023–2025, composite reference for phase change material (PCM) integration studies in solar cold storage.

[51] E. d. S. Garcia, N. Quaresma, Y. B. Aemro, A. P. Coimbra, and A. T. de Almeida, “Cooling with the sun: Empowering off-grid communities in developing countries with solar-powered cold storage systems,” *Energy Research & Social Science*, vol. 117, p. 103686, 2024.

[52] S. Vijayakumar, A. Mani, and S. Advaith, “Development and performance evaluation of solar absorption cold storage system for tropical climates,” *Solar Energy*, vol. 279, p. 112822, 2024.

[53] Various authors, “Additional nutritional impact studies from ifpri and related works,” 2021–2024, composite reference drawing from IFPRI studies and related nutritional impact assessments.

[54] Z. Ouaouja, A. Ousegui, C. Toublanc, O. Rouaud, and M. Havet, “Phase change materials for cold thermal energy storage applications: A critical review of conventional materials and the potential of bio-based alternatives,” *Journal of Energy Storage*, vol. 110, p. 115339, 2025.

[55] Y. Rami and A. Allouhi, “Design, economic, and environmental accounting assessment of a solar-powered cold room for fish storage in traditional markets,” *Sustainability*, vol. 16, no. 7, p. 3080, 2024.

[56] Various authors, “Ongoing trends from recent 2024–2025 publications on solar refrigeration scalability,” 2024–2025, composite reference for emerging trends and scalability in solar-powered refrigeration systems.

[57] ASHRAE, *2014 ASHRAE Handbook–Refrigeration*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2014.

[58] C. D. Pero, F. M. Butera, M. Buffoli, L. Piegari, L. Capolongo, and M. Fattore, “Feasibility study of a solar photovoltaic adaptable refrigeration kit for remote areas in developing countries,” in

2015 International Conference on Clean Electrical Power (ICCEP), Taormina, Italy, Jun 2015, pp. 701–708.