DESIGN AND PERFORMANCE EVALUATION OF AN OIL/ROCK BED HEAT STORAGE SYSTEM FOR SOLAR COOKING

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Abstract

This thesis presents the development and performance evaluation of a sensible thermal energy storage system that used sunflower oil and rock pebbles as heat storage mediums. The aim was to assess the system's performance based on charge and discharge rates, energy storage capacity, power output, cooking efficiency, and cost-effectiveness. The main body of the system was created with an old hot water geyser. An Arduino-based data logger was fabricated and was used to monitor and capture temperature changes throughout system operation periods. The data was analyzed with Python programming, from which time-temperature graphs were drawn. The heat retention capacity was obtained by heating the system to about 200 °C and then cooling it, with the time taken to cool being recorded. The system took approximately 30 hours to cool from 194°C to 60°C. The system generated 0.028 kW of power and stored a total of $0.85\ kWh$ of heat energy. The efficiency testing, which involved boiling five liters of water, yielded an average efficiency of 78.98%. The total cost of constructing the system was: N$ 3,860, with a unit energy cost of N$ 1.26/kJ and a unit power cost of N$ 137.86/W. The cooking test demonstrated that the system could simultaneously cook 300 g of rice in 43 minutes and 300 g of dry beans in about 4 hours using only the stored thermal energy. The study therefore concluded that the developed system was able to deliver a reliable and cost-effective solution for domestic use. Nonetheless, constraints including insufficient funding for further development and a limited timescale, impeded comprehensive investigation of the system's capabilities. Future research needs to improve the design of the system as well as explore the possibility of using solar PV panels to heat the TES system.

Keywords: Thermal energy storage, Oil/rock bed, Solar cooking, Solar energy, Heat energy, Arduino data logger

List of Publication(s)/Conference(s) Proceedings

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List of Abbreviations and/or Acronyms

$\Delta \boldsymbol{T_s}$	Temperature change in the storage
$\Delta \boldsymbol{T_w}$	Temperature change of water
$\boldsymbol{c_{oil}}$	Specific heat capacity of sunflower oil
$\boldsymbol{c_{rocks}}$	Specific heat capacity of the rock pebbles ‘granite’
$\boldsymbol{c_w}$	Specific heat capacity of water
$\boldsymbol{k_{ins}}$	Thermal conductivity of the insulation ‘Glasswool’
$\boldsymbol{m_{oil}}$	Mass of sunflower oil used
$\boldsymbol{m_{rocks}}$	Mass of the rock pebbles used
$\boldsymbol{m_w}$	Mass of water
$\boldsymbol{\rho_{rocks}}$	Density of rock pebbles ‘granite’
$\boldsymbol{\rho_w}$	Density of water
CSCs	Concentrating solar cookers
CSP	Concentrated Solar Power
ETCs	Evacuated Tube Collectors
FPCs	Flat Plate Collectors
HTF	Heat Transfer Fluid
LTES	Latent Thermal Energy Storage

MPPT	Maximum Power Point Tracker
NTNU	Norwegian University of Science and Technology
PCMs	Phase Change Materials
PV	Photovoltaic
RTC	Real-Time Clock
SHMs	Sensible Heat Materials
STES	Sensible Thermal Storage
TCTES	Thermochemical Thermal Energy Storage
TES	Thermal Energy Storage
UNAM	University of Namibia

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Dedication

This work is dedicated to my younger siblings: Sam, Salom, Sandra Hauwanga as well as Ananias, Bonifatius, Tresia, Jonh, Kenedy and Megameno Naule.

Declarations

I, Cecilia Ndafaanhu Naule, hereby declare that this study is my own work and is a true reflection of my research, and that this work, or any part thereof has not been submitted for a degree at any other institution. No part of this thesis/dissertation may be reproduced, stored in any retrieval system, or transmitted in any form, or by means (e.g. electronic, mechanical, photocopying, recording or otherwise) without the prior permission of the author, or The University of Namibia in that behalf. I, Cecilia Ndafaanhu Naule, grant The University of Namibia the right to reproduce this thesis in whole or in part, in any manner or format, which The University of Namibia may deem fit.

Cecilia Ndafaanhu Naule	Naule	October 2025
Name of Student	**Signature**	**Date**

Chapter 1: Introduction

1.1 Background of the study

1.1.1 The history of solar cooking

The history of solar cookers indicates an increasing dedication to sustainable energy solutions, extending back to the 18th century, when early pioneers experimented with the sun’s heat for practical applications. The box-type solar cooker established in the 1760s by Swiss scientist Horace de Saussure, provided the framework for solar cooking as an effective, low-cost cooking alternative [1,2,3,4]. De Saussure's discovery encouraged later research and optimization efforts in solar cooking devices.

Solar cookers gained popularity in the mid-twentieth century as a technique for solving energy scarcity and environmental issues in underdeveloped countries. These devices provided a substitute for traditional biomass-based cooking techniques, therefore lowering indoor air pollution and deforestation. Popular at this time were box-type and parabolic solar cookers, with their improvements motivated by simplicity, cost-effectiveness, and local adaptability [4,5]. Efforts during this period was looking to maximize thermal performance while preserving cost. The goal was to make solar cookers accessible to rural homes with limited energy resources.

In recent decades, solar cooker development has progressed from simple versions to more complex designs integrated with tracking systems and thermal storage capacities. Sun-tracking solar cookers, for example, have received much research because they maximize efficiency by staying in line with the sun's path throughout the day [2,4,6,7,8,9,10]. Studies indicated that these technologies have both economic and environmental benefits, particularly when employed at community-level cooking systems.

Concentrating Solar Cookers (CSCs) are a notable breakthrough in the sector [1,5]. These devices focus solar energy using mirrors or lenses, resulting in higher temperatures appropriate for industrial uses such as cooking thousands of meals each day [4]. The examination of these CSCs' performance demonstrates their applicability for institutional and industrial operations. However, their implementation raises economic, operational, and maintenance challenges.

Solar cooking solutions have faced criticism for overlooking cultural, social, and contextual elements in their design and implementation. For instance, a discrepancy between the technically required parameters and the parameters that are most effective for the user's requirements is likely to arise as a consequence of assumptions regarding the user's behavior and cooking patterns. The incorporation of user feedback into the development process is thus crucial for improving adoption [11]. Another critical challenge hindering the widespread use of solar cookers is the lack of heat storage capacity to enable cooking at night or when the sun is not shining; this is attributable to the fluctuating pattern of solar radiation [12].

Hybrid solar cookers, equipped with thermal energy storage (TES) devices, are some of the new developments in this sector [12,13]. These solar cookers store heat in phase-change materials or oil-rock beds, therefore extending their usage to non-sunny periods. Existing studies on TES have shown the effectiveness of the systems in providing a long cooking period, in addition to improving the effectiveness and feasibility of the solar cooking technologies. The general classification of solar cookers is shown in **Figure 1** below [5].

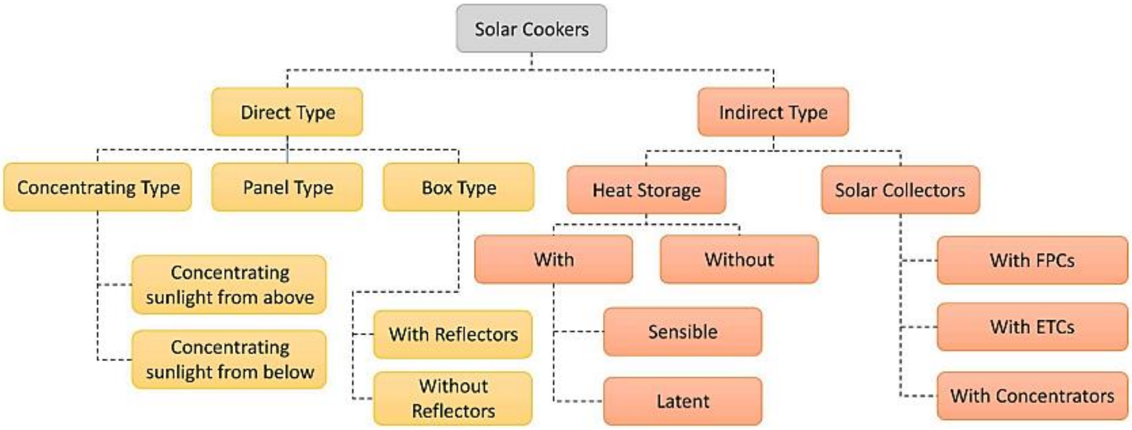


Figure 1: *General classification of solar cookers*

Another obstacle facing solar cookers, despite developments in TES systems, is their often-bulky nature and design configurations that do not conveniently facilitate indoor cooking. This results in little deployment and adoption by end users. Thus, recent studies have explored the feasibility of utilizing solar photovoltaic (PV) technology for cooking [14].

The most recent advancements in photovoltaic conversion to electrical power emphasize induction and resistive pressure cookers [14,15,16,17]. In contrast to traditional solar cooking methods that depend on direct solar thermal conversion, photovoltaic cooking operates indirectly by initially transforming sunlight into electricity [16,17].

The generated electric energy may be stored in batteries for further utilization during times of inadequate irradiance [18,19]. In indirect solar cookers, researchers physically separate the cooking vessel from the solar collector and use a medium to convey the collected energy to the cooking container [17,18,20]. Examples are cookers utilizing flat plate collectors (FPCs), evacuated tube collectors (ETCs), and concentrating-type collectors

[5,15]. These necessitate a thermal storage medium, which may be either LTES or STES [21].

Joshi and Jani [22] transformed a box solar cooker into a hybrid photovoltaic-thermal cooker, using five photovoltaic panels, each rated at 15W. The photovoltaic panels were linked to an electrical heater within the oven. Their findings demonstrated that the enhanced system decreased cooking time by integrating the photovoltaic impact with the thermal effect. The revised system exhibits a 38% enhancement in efficiency and has the capacity to prepare up to five meals daily [22].

Further research [20], devised a photovoltaic (PV) solar cooker. Their system had three components: a photovoltaic panel affixed to a support structure, an insulated cooking pot modified to replace its internal heating plate with a new one featuring an integrated heating circuit that also served as heat storage, and a basic circuit board that regulated the panel to optimize Maximum Power Point Tracking (MPPT). The results indicated that the device necessitated 1.5 hours to boil 2 liters of water, which was maintained in the covered pot while the cooking unit was disconnected from the solar source. The boiling water took 20 hours to attain room temperature, demonstrating the system's capacity to cook or boil food in the absence of a power source.

Khan and Alam [21] similarly presented a grid-integrated cooking solution with a solar PV-based inverter-less system. The system incorporated a control circuit that linked electricity from grid to the solar PV via a DC link. This delivered a DC output and obviated the need for grid-connected inverters. The solar PV system was designated as the primary power source, with the grid serving as a backup during fluctuations in solar production caused by changing weather conditions. The system's absence of a grid-tied converter hinders the transmission of surplus solar energy into the grid, prompting the innovative concept of storing solar photovoltaic energy as hot water. The test findings indicated that the cooking expenses associated with this system were around 32% cheaper than those of grid-based cooking while simultaneously reducing grid energy usage by roughly 78% [21], therefore establishing it as a cost-effective option. **Figure 2** shows the modern classification of solar cookers [15].

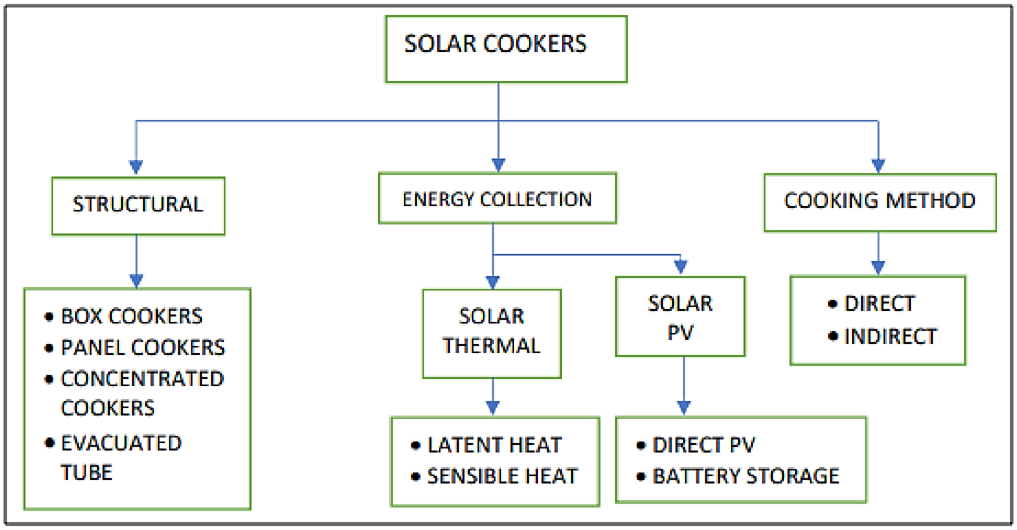


***Figure 2**: Modern classification of solar cookers*

1.1.2 Overview of thermal energy storage systems

TES systems are a significant innovation in solar cooking, designed to address the intrinsic unpredictability of solar energy. TES may be utilized in solar cookers to accumulate heat during sunny intervals and subsequently discharge it during overcast conditions or at night, hence enhancing the dependability and versatility of solar cookers [13,23].

Solar thermal often employs Latent Thermal Energy Storage (LTES), Sensible Thermal Energy Storage (STES), or Thermochemical Thermal Energy Storage (TTES) techniques for thermal energy storage [13,23,24,25,26]. Sensible heat storage materials retain and discharge heat via temperature fluctuations, these includes water, oil, and rocks [13,24]. These materials are inexpensive and user-friendly, although their energy-to-volume density is quite low. Okello et al. detailed the incorporation of a thermal energy storage unit employing sensible heat storage with a cooking component, which enabled continuous cooking when the system is not charging [23]. Different energy storage technologies are presented in **Figure 3** [27].

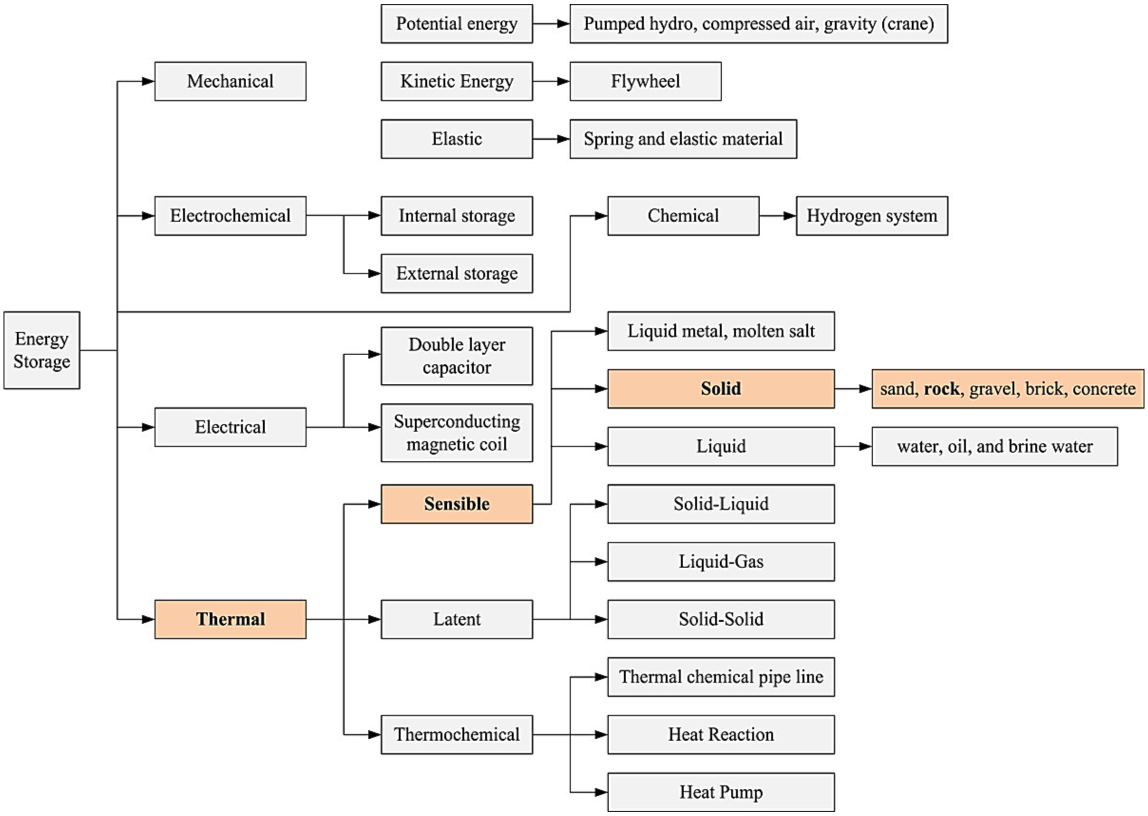


Figure 3: *The different energy storage technologies*

Latent heat storage, on the other hand, employs Phase Change Materials (PCMs) to be able to retain energy during phase change from one state to the other for instance from solid to liquid. PCMs have a higher energy storage density and are suitable for operating in certain temperature levels that are suitable for cooking. A study by Patel and Patel [25] supported the use of PCMs such as paraffin wax in solar cooking, and demonstrated how it can sustain high cooking temperatures for many hours. Nevertheless, factors like cost of the material and thermal characteristics are still critical to the PCM choice [25,28].

The efficacy of solar cookers with TES is contingent upon the design and integration of TES systems. A study by Saxena and Karakilcik [26] showed that low-cost TES materials used together with insulated enclosures enhance the cooking efficiency by minimizing heat losses. Likewise, Nkhonjera et al. [24] considered various TES designs and innovations such as the encapsulated PCM units and the STES and LTES hybrid.

The geometry of TES systems is also an important factor influencing the systems' performance. Cylindrical, spherical, and layered arrangements have been used to improve heat transfer and reduce energy dissipation [29,30,31,32]. Suresh and Saini assessed the effects of geometrical designs and established that system designs with larger surface area to volumes ratio have a better heat transfer co-efficient, which is a crucial characteristic of effective and efficient solar cooking systems [29].

Further development has also been made towards TTES systems which use chemical reactions in the storage and/or retrieval of energy [33,34]. Although these systems promise long term storage and high energy density [28,34], they are complicated and expensive and can therefore not be used for household cooking.

Therefore, the introduction of TES systems has enhanced solar cooking by responding to its temporal challenges. These systems provide dependable cooking solutions utilizing modern heat storage materials and novel designs to meet the increasing trend of sustainable and energy-efficient technologies.

1.1.3 Introduction to data loggers

Temperature ranks among the five most frequently measured parameters globally, driving annual advancements in measurement devices for both minute and large-scale applications [35]. In the contemporary world, virtually all systems require some type of temperature monitoring, and the measurement precision provided by today's most sophisticated temperature data loggers competes with that of many more expensive, computer-based data collecting systems [36]. Furthermore, the necessity for acquiring high-quality data escalates significantly, as enhanced knowledge on performance could improve knowledge of the dynamics of system energy use, thermal comfort, indoor environmental quality, and the microbiology of the built environment, among others.

Modern management systems may collect considerable data on operations; nevertheless, accurate characterizations of some metrics often depend on proprietary hardware/software, adversely affecting costs, flexibility, and data integration in decision-making and control [36]. Measurement in the engineering organizations is strictly regulated by the accuracy and effectiveness of measuring devices. This further affects the increased selling price of measuring devices (sensors), data collection systems, or data loggers produced by measurement equipment manufacturers. Many laboratories in educational institutions lack the instrumentation for these measuring instruments due to their high cost [37].

A data logger is a programmable electronic device that facilitates the measurement, documentation, analysis, and authentication of numerous parameters, such as voltage, current, humidity, temperature, and pH, over a specified duration with desired time intervals. The fundamental requirements for a data logging system are collection, online analysis, logging, offline analysis, presentation, and data exchange [35]. Data loggers receive data inputs from sensors integrated into the circuit, contingent upon the intended use and the parameter being monitored. Typical examples of these input sensors are temperature sensors, sound sensors, pressure sensors, flame sensors, light sensors, electrical sensors, touch sensors, water sensors, and fire sensors [35].

The primary components of a data logger include a microcontroller (such as an Arduino, Universal Synchronous/Asynchronous Receiver/Transmitter (USART), microprocessor, Peripheral Interface Controller (PIC), or Integrated Electronics (INTEL) 8051, 8052, AT89s52); a sensor for value acquisition; Serial Data (SD) for internal data storage; and a power supply system (e.g., battery, Universal Serial Bus (USB), or alternating current supply) [38,35,39,40,41]. It operates with the sensors that transform physical events into electrical impulses. Subsequently, these electrical signals are transformed into binary data, which may be readily evaluated by software and saved for future processing examination [39].

The primary advantage of data loggers compared to some measuring devices is their capacity to autonomously record data for a designated timeframe, subject upon their power supply [35]. This function reduces human involvement in inspection and inaccuracies in the recording and documenting of values. Various types of data loggers exist, including Wi-Fi data loggers, universal input data loggers, Bluetooth data loggers, remote data loggers, Radio Frequency Identification data loggers, Modbus data loggers, high-speed data loggers, multi-channel data loggers, paperless data loggers, and mechanical and electrical data loggers [35].

A multitude of factors may influence the selection of a data logger, including reliability, cost, usability, timeliness, high data accuracy, efficiency, alarm indication for preferred value limits, capacity to endure elevated temperatures in hot environments, and available storage space, among others [35,42]. The compact size of a datalogger system confers mobility as one of its advantages. A further benefit is the capability of autonomously gathering data over extended periods without human oversight [35,40]. Datalogger systems are tailored to meet the requirements of certain configurations or applications. Furthermore, they are applicable in isolated locations or hazardous circumstances. They exhibit greater accuracy due to the absence of potential human mistake in the recording process. They aid in the comprehension of scientific concepts and experiments by providing visual aids derived from their records [40].

While dataloggers offer many benefits, they also have significant drawbacks. Their costs are high, and the initial investment is substantial for small enterprises [40]. Typically, they lack all the functionalities demanded by the user, necessitating modifications to the software or application. Consequently, certain data may be lost or unsaved in the event of a data logger malfunction. Furthermore, certain dataloggers are capable of recording measurements solely at the preconfigured defined intervals. Moreover, fundamental training is necessary for their utilization [40]. As a result, it is essential to create economical, user-customizable, and reprogrammable datalogger systems tailored for specific objectives to accurately record the needed information.

In recent years, several researchers have utilized Arduino as a mechanical controller or for data acquisition [37]. An Arduino is a tangible programming platform that employs Advanced Technology for Memory and Logic (ATMEL) microcontrollers and features various digital and analog inputs and outputs [43,40]. A microcontroller is a compact computer encapsulated within a single integrated circuit, comprising a CPU, memory, and programmable input/output peripherals [38]. The Arduino platform integrates electrical hardware and software into a unified system that is accessible for beginners across several applications, including laboratory and field research [43]. Arduino detects environmental conditions via input from several sensors and modifies its surroundings by controlling lights, motors, and other actuators.

Instances of utilizing Arduino as a mechanical controller encompass stepper motor drives and data collection time configurations determined by frequency or duration [37]. Arduino may function as a data gathering device to collect temperature readings with thermocouples. Besides data collection, Arduino may operate as an independent data logger with an extended data retrieval period. Arduino can obtain data from 64 temperature sensor points by employing a multiplexer to interface various devices [37]. The Arduino's notable advantage is in its cross-platform Integrated Development Environment (IDE), which offers a streamlined C++ programming interface that utilizes comprehensive code libraries, eliminating the necessity for users to understand low-level specifics for typical implementations [43].

An Arduino-based data logger possesses several attributes, including the utilization of inexpensive components relative to commercial data loggers, which are often costly; these components are readily accessible for procurement. Minimal power consumption; The flexibility of operational settings; The capability to interface with a computer for data collection and analysis [39]. Recent developments in the energy sector indicate that the solar energy industry is among the fastest-growing renewable energy sector globally.

Currently, there is a substantial increase in demand for remote monitoring and control technology for solar energy applications [44]. The necessity for this data logger project emerged from the inaccessibility of temperature loggers for many researchers in underdeveloped nations, attributed to the excessive prices of these systems and the widespread challenges in securing funding in these areas.

This project chose an Arduino data logger because of its open-source character, simplicity of use, and great community support. The modular architecture of the platform enables simple integration of other components including sensors, shields, and displays as well as its capacity to be driven with a tiny power bank in case of distant/remote places where a computer cannot run it. This adaptability makes Arduino a great alternative for bespoke data logging solutions fit for particular requirements. Furthermore, the large spectrum of accessible libraries streamlines the development process and makes fast prototyping and implementation possible. This work therefore produced a tailored and re-programmed datalogger system ready for measuring four temperature values from a heat storage energy system.

1.2 Statement of the problem

In spite of the surplus solar energy in Namibia, there are still uncertainties towards the use of solar cookers, mainly because of their inability to store energy for cooking during non-sunshine hours, thus limiting their adoption as a sustainable cooking method.

Although a number of researchers have explored heat storage systems for solar cookers and have proved promising results [26,45], there remain a wide gap regarding this topic in Namibia. This therefore necessitated a need to locally develop a heat storing system that can efficiently store thermal energy, using locally available materials, and is suitable for Namibian cooking habits.

1.3 Objectives of the study

This research aimed to achieve the following objectives:

a) Design an oil/rock bed thermal energy storage system
b) Construct the designed thermal energy storage system
c) Develop an Arduino-based data logger for data collection
d) Evaluate the thermal performance of the developed thermal energy storage system

1.4 Significance of the study

Firstly, the findings of this research enriched the increasing body of knowledge on thermal energy storage systems, particularly the utilization of oil and rocks as heat storage mediums for cooking applications. Secondly, by promoting the use of renewable energy technologies, this study could contribute to Namibia’s National Development Plans.

1.5 Limitation of the study

This research encountered difficulties that impeded a comprehensive investigation of its potential outcomes. A primary restriction was the lack of financial resources, which restricted the acquisition of essential components, such as a parabolic reflector or photovoltaic panel. These components would have facilitated an evaluation of the system's capacity for direct heating using solar energy. While another heating technique was used in this study, the breadth of direct solar application was constrained.

Moreover, the research was conducted within a constrained timeframe, despite the substantial time required for the development and testing of TES system. The rigidly established schedule constrained opportunities for doing cycle testing and system validation. Additional research with sufficient funding and extended durations is necessary to address these deficiencies, enabling a comprehensive assessment of system efficiency under varying operating situations.

1.6 Delimitation of the study

The study exclusively concentrated on the use of sunflower cooking oil and rocks (pebbles) as heat storage materials. This is because oil/rock pebbles have been proven to have a high efficiency as compared to other heat storing medium and sunflower oil it is locally available at an affordable price in addition to free pebbles.

Chapter 2: Literature review

2.1 Introduction

This section provides a summary of the literature on the principles, applications and development of TES systems. It presents several TES techniques, with emphasis on sensible heat storage and the oil/rock bed technology and its suitability to small scale cooking applications. The chapter further emphasizes the utilization of data logging technologies, including Arduino-based systems, to improve the assessment of TES performance. By identifying research gaps and opportunities, this chapter provides the foundation for the design and development of an oil/rock bed TES system appropriate for Namibian cooking habits and based on locally accessible materials.

2.2 Three main types of thermal energy storage systems

TES systems can be grouped based on their operational temperature range, storage method, circulation type, and storage duration [29,46].

TES systems are classified according to their working temperatures into low, medium, and high-temperature categories. Storage systems functioning within the temperature range of 20-100°C are classified as low-temperature storage; those operating within the range of 100°C to 200°C are categorized as medium-temperature storage systems, and systems exceeding 250°C are designated as high-temperature thermal storage systems [29,46]. Heat Transfer Fluids (HTF) are crucial for transferring thermal energy from heating apparatus, and the selection of the HTF is determined by the operational temperature range of the TES system [29].

TES systems fall into three main groups according to their storage mechanisms and these are: sensible thermal energy storage (STES), latent thermal energy storage (LTES), and thermochemical storage (TCTES) [29].

TES is also categorized according to the characteristics of HTF circulation. It may be categorized as an active TES system or a passive TES system. An external device (pump) circulates the storage material via the heat exchanger (solar receiver) in an inactive TES system, causing energy absorption or release through forced convection [29].

Active TES can be categorized into direct and indirect forms. In a direct TES, the storage material functions as both the HTF and the energy storage medium, conversely with an indirect TES, the storage media remains stationary, and the HTF is responsible for the transportation of heat energy from the source to the storage medium in order to retain energy. In a passive TES, the heat transfer fluid flows through the storage medium only by gravity or buoyancy forces, without the aid of any external equipment [29,46].

TES are further categorized based on their storage duration. They are classified into short-term and long-term storage. The TES system undergoes daily or weekly charging and discharging for short-term energy storage to satisfy energy demands during overcast conditions and peak use times. Short-term storage is appropriate for solar cooking apparatus.

2.2.1 Latent Thermal Energy Storage systems

LTES systems are recognized for possessing the prospect of enhancing the performance and dependability of solar cooking uses. These systems employ PCMs that store heat energy when the material undergoes phase change, often from solid to liquid, and subsequently release the accumulated energy as the material solidifies again [28,29,46]. LTES systems are especially beneficial and less costly because they have the capacity to store a substantial quantity of energy in a limited volume while retaining nearly constant temperatures throughout phase changes [47]. This feature is essential in any applications that need a constant heat supply.

The thermal energy stored by LTES can be expressed as [29,46]:

$$Q = mL \tag{1}$$

In this context, m represents the mass of the heat storage medium (Kg) and L denotes the specific latent heat (kJ/Kg).

More detailed equations are given by equation (2)

and (3) below [25, 28].

$$Q = \int_{T_i}^{T_m} m\, C_p dT + m a_m \Delta h_m + \int_{T_m}^{T_f} m\, C_p dT \tag{2}$$

$$Q = m[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_m)] \tag{3}$$

Where:

T_m is the melting temperature (°C), T_i, T_f represents the initial and final temperatures (°C), m signifies the mass of the PCM medium (kg), C_{ps} indicates the average specific heat of the solid phase between T_i and T_m (J/kg.K), a_m refers to the fraction melted , Δh_m is the latent heat of fusion per unit mass (J/kg) and C_{lp} denotes the mean specific heat of the liquid phase between T_m and T_f [25,28].

LTES systems employ PCM as the storage material. This possesses the advantage of being isothermal during charging and discharging processes, which in turn leads to the miniaturization of the container and therefore the construction cost [28,29].

Two factors determine the classification of PCMs: the transition temperature value and the applications of PCMs. They include the organic, inorganic, and eutectic materials, which are shown in **Figure 4** [28]**.**

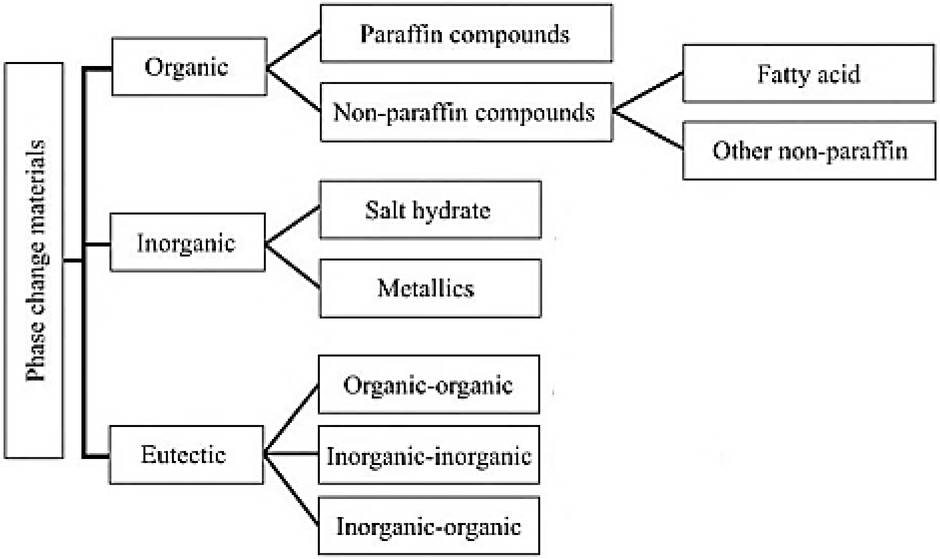


Figure 4: *Classification of PCMs*

Researchers have explored a variety of PCMs for LTES applications, with paraffin wax garnering the most attention due to its affordability, non-toxicity, suitable melting temperature range, low supercooling, nonflammability, compatibility with metal containers, chemical stability, and lack of phase separation [28,46,48]. However, it has low thermal conductivity and is thus not suitable for use in cooking applications.

Fatty acids and salt hydrates are also often used because they have many benefits, such as better heat transfer rates and higher thermal conductivity, has a wide variety of melting points and desirable transition temperatures [48,49,50,51,52]. Besides rusting, many fatty acids are poisonous or emit hazardous vapors at high temperatures. Salt hydrates encounter issues such as reduced thermal stability, chemical instability, metal corrosion, inconsistent melting, and sub-cooling beneath the solidification temperature [52].

Agarwal and Sarviya [53] developed a solar dehydrator that utilize paraffin wax as a heat storage PCM. According to their test results, the paraffin wax storage was appropriate for providing hot air to dry food during periods with no sunlight or when intensity of solar energy was very low. The temperature increase of air during discharge ranged from 19°C to 5°C during a duration of roughly 10 hours.

Tesfay et al. [50] conducted research that demonstrated the effectiveness of latent heat storage in delivering consistent cooking performance. The research created a storage-integrated solar fryer capable of holding 20 kg of solar salt, a nitrate salt combination of 40% KNO_3 and 60% $NaKO_3$. The storage system consisted of a connected polar-mounted concentrator, with a stationary receiver and steam heat transfer fluid. Steam flowed spontaneously in a closed loop between the evaporator and condenser. The TES was capable of retaining heat for nearly two days and reached temperatures of around 250ºC [50].

Equally, Pawar et al. [49] pointed out that the incorporation of LTES systems into solar cooking improve the efficiency of the systems. In their study, they demonstrated an urban solar cooking system that stored heat using commercial-grade erythritol as a primary carbon medium. The system was designed to prepare meals twice daily for 4 people, amounting to 5000 kJ, with the heat exchanger employed to control heat transmission from the storage tank to the cooking vessel. These experiments confirmed the possibility of cooking twice a day and also assessed the performance capability of the enhanced solar cooker to be as good as the domestic LPG stove [49].

A further investigation by Vigneswaran et al. [51] examined the feasibility of using Oxalic acid dihydrate as a PCM in a solar box cooker showcased increase in cooking time and thermal efficiency as well. Oxalic acid was selected because of high a specific enthalpy and its melting point which is near to the cooking temperature. Cuce et al. [54] expanded this approach by adding booster reflectors to a box solar cooker utilizing natural beeswax product derived propolis waste. Propolis is a complex substance employed for the construction of beehives and for protection against either climate fluctuations or diseases [54].

While groundnut oil primarily serves as a sensible heat storage material, researchers have also explored its potential for use in latent heat storage. Maina et al. [55] tried it on a solar box cooker and observed enhanced cooking performance in different weather and identified the possibility of its use as an effective and low-cost PCM [55].

However, some of the issues that arise with LTES systems are low thermal conductivity, toxicity, leakage (whether in the liquid or the gas state), and also the high cost of some PCMs [22,47,52]. PCMs often exhibit limited heat conductivity and prolonged periods of charging and discharging the same amount of energy, meaning that they cannot be used extensively, especially for domestic use such as cooking [56]. New trends in encapsulation include the use of metal or polymer shells to overcome challenges that are associated with leakage and thermal degradation of the PCMs [47,48,52]. These are critical innovations that help enhance the life span and efficiency of LTES systems. Researchers also explore the integration of latent and sensible heat storage materials, and enhance PCMs by incorporating additives such as nanoparticles [29,57,58].

2.2.2 Thermochemical thermal energy storage systems

TCTES systems have the capacity to store energy by means of reversible chemical processes. Their high energy density, long-term storage capacity, high operating temperatures, and low heat loss during storage periods [29,33,59], make them the most promising for Concentrated Solar Power (CSP).

TCTES systems work by using thermochemical cycles that may be endothermic during charging and exothermic during discharging. Chemical bonds hold the stored energy and is released after the reaction has been initiated in the reverse process [33,60]. Some of the reactions include the hydration and dehydration of metal hydroxides, the oxidation and reduction of metal oxides, and decomposition [33,60,61]. The advantage of chemical storage is that there is no need to insulate the chemical energy storage system [34], unlike LTES and STES systems.

Discharging processes for TCTES systems exploits the exothermic pathway of the reversible reaction depicted in equation **(4**) below [34]:

$$C + \Delta H \leftrightarrow A + B \tag{4}$$

Where, C is the thermochemical substance that absorbs energy ΔH which is then chemically transformed into distinct parts A and B. ΔH represents the enthalpy change of the reaction. Parts A and B may be stored independently - either at ambient or operational temperature, so preserving the energy received by C for its dissociation processes. Upon the recombination of A and B, C is recreated, and the previously stored energy is discharged; this released energy is the restored thermal energy from the system. Therefore, the reaction's heat during the formation of material C represents the storage capacity of the TCTES system [34].

The thermal energy stored Q(J) in thermochemical material C is given by Equation **(5)**, where n_C denotes the number of moles of C and ΔH signifies the reaction enthalpy (J/mol) [34].

$$Q = n_C \Delta H \tag{5}$$

Researchers have studied a variety of materials for TCTES systems. These includes: metal oxides, hydrated salts, as well as ammonia and methane derivatives. Among these materials, copper oxide, manganese oxide, cobalt oxide, and iron oxide are commonly investigated because of their high working temperature and thermal stability. These are especially appropriate for high-temperature use in industrial processes [33,59,60].

Magnesium hydroxide and Calcium hydroxide also find importance in extreme temperature applications and chemical heat pumps. The latter was specifically found to be particularly useful in the CSP due to the constant production of heat during the hydration of the material [33,62]. Applications requiring high energy density employ derivatives of ammonia and methane. Their reversible decomposition demonstrates enormous potential for solar thermal energy storage [34,63].

However, TCTES systems experience the following challenges: First of all, multiple reaction cycles negatively impact the storage capacity and the overall lifetime of some of the materials [33,34,59,60]. Secondly, slow reaction rates especially in large-scale systems make the application of TCTES for immediate use not feasible [34,60,61]. Finally, high costs of the development of advanced thermochemical materials, along with costs related to the integration of the system limit its application [34].

Future work therefore seeks to overcome these challenges by designing new materials that have higher reaction rates, better stability, and lower cost. Furthermore, improvements in system design, including modular reactors and hybrid systems, could improve the viability of TCTES [64].

2.2.3 Sensible Thermal Energy Storage Systems

The most developed and popular TES option is STES systems, which are characterized by their simplicity, cheap prices, and ease of integration in solar thermal applications like solar cookers and solar stills [23,59,65,66]. Therefore, they are a suitable option for low-income countries. Besides, sensible heat materials (SHMs) typically exhibit greater heat conductivities than PCMs in solar energy systems. The high thermal conductivity of SHMs is advantageous for effective heat transmission during charging and discharging [56].

In STES, heat is absorbed by rising the temperature of a liquid or solid media such as oil, water, sand, or concrete without changing its phase [65,66]. The heat is then dissipated by reducing the medium's temperature. The heat energy stored depends on specific heat capacity, mass of the material and the temperature difference [59], it is expressed by the following equation **(6)** [59,28].

$$Q = \int_{T_i}^{T_f} mC_p dT = mC_p\,(T_f - T_i) \tag{6}$$

Here, Q denotes the quantity of heat stored (J), T_i, T_f are the beginning and final temperatures (°C), m specifies the mass of the storage medium (kg) and C_p indicates he specific heat capacity of the storage medium (J/kg.K).

STES systems employ concrete, iron, molten salts, sand, rocks/pebble for thermal storage and air, water and oils as heat transfer fluids (HTFs) [13,23,28,65,66,67,68,69,70]. For example, Milikias et al. [45] employed sensible heat storage materials, specifically black stones and concrete, to improve the efficacy of a box solar cooker. Findings demonstrated that the enhanced box cooker significantly outperformed a traditional box cooker, with the materials utilized capable of retaining heat for 5 hours (18:00–22:00) at temperatures above 70ºC, thereby facilitating food warming over this interval. Likewise, Saxena and Karakilcik [26], evaluated the performance of a box solar cooker which consisted of a combination of sand and granular carbon as heat storage materials. The research demonstrated that the heat storage technology was viable for cooking food during times without sunlight, with the cooker attaining a cooking efficiency of around 37%.

Niksiar et al. [69] evaluated the thermal efficacy of silica sand as a heat storage medium in a shell-and-tube seasonal TES system utilizing water as the HTF. The researchers examined two varieties: fine sand and coarse sand, ascertain which one was most effective for heat transfer and storage. The fine sand, which consists of smaller particles than the coarse sand, improved thermal transmission inside the system. The research findings indicated potential for improving TES in applications aimed at energy efficiency, particularly in CSP and industrial waste heat recovery. Utilizing silica sand as a storage media offers a cheaper and plentiful alternative to traditional TES materials, rendering this technology appropriate for extensive heat storage requirements where economic and material efficiency are paramount.

Researchers have conducted numerous studies using air and rock-packed bed as TES systems [28,56,67]. Air exhibits low thermal conductivity and requires a bigger volume to store adequate energy for TES due to its considerable expansion and low thermal capacity [56]. Likewise, air thermal energy storage devices need substantial pumping power to accumulate significant heat quantities. Investigations have been undertaken on thermal energy storage devices utilizing water in order to address the deficiencies in air systems [28,56]. The greater specific heat capacity, widespread availability, chemical stability, and low cost make water an efficient storage medium for low-temperature outdoor cooling applications, including single-stage absorption chillers and desiccant systems [28].

Nevertheless, water fails to stratify well in basic storage tanks lacking appropriate stratification mechanisms. Stratification devices have the added effect of increasing the costs of the TES. Moreover, water faces the challenge of evaporating at temperatures above 100 °C. This necessitates the utilization of pressurizing apparatus for water to function at temperatures beyond its low boiling point. Because of this limitation (100 °C), application of water as a STES medium for intense heat use requires enhancement of the system pressure [28,56]. Operating beyond the boiling point of water entails increased expenses for heat exchangers and technical procedures.

Thermal oils have been used to store thermal energy in storage systems because of the low conductivity of air and lower boiling point of water. For example, Nydal [71] demonstrated three concepts, which were: a fryer with a PCM and thermal oil as a HTF, an oil-based one-tank system that employed thermal oil as a storage medium, and a three-tank oil-rock bed system that employed thermal oil as a HTF.

Research, however, revealed that thermal (mineral) oils are principally appropriate for heat storage in power plants. They are not suitable for domestic uses due to their high degradability, flammability, cost, and emission of hazardous fumes, particularly at high temperatures [56]. Due to the costly and toxic characteristics of the commercial thermal oils, it becomes mandatory to utilize locally sourced vegetable oils [56,65,71].

Research on temperature-dependent thermal characteristics of several edible oils revealed that sunflower oil had a high specific heat capacity and a broad operational temperature range [56,65,72]. They also recognized that the viscosity of sunflower oil remained minimal at severe temperatures, facilitating smooth circulation [56,72].

Tabu et al. [72] performed an investigation on the thermal efficiency of certain oils in Uganda for cooking purposes using indirect solar application. The used oil samples consisted of refined palm oil, refined sunflower oil, and thermia B. Their findings demonstrated that thermal stratification of sunflower oil exceeded that of the other two. The stored energy and exergy of refined sunflower oil were also typically superior. Additionally, the thermal performance of sunflower oil was equivalent to that of palm oil, which surpassed that of thermia B [72].

It is further observed that sunflower oil has a high temperature-dependent density and specific heat capacity, as well as elevated charging power. Moreover, its flash point is about 250 °C, which exceeds the cooking temperature of most meals. Alternative edible thermal oils with relatively low viscosities at ambient temperature, such as coconut oil, may be utilized; nevertheless, sunflower oil is favored due to its cost-effectiveness, accessibility, and extensive application in nations like Namibia [65].

This implies that sunflower oil has a better heat transfer characteristic than other oils at high-temperatures and low charging flow rates. It is therefore considered a better thermal oil alternative when charging at higher temperatures and low flow rates. This suggests that a higher flow rate for sunflower oil results in a shorter charging time for the TES system, and vice versa [56,65].

Mawire [65], assessed the thermal characteristics of sunflower oil for heat storage in household cooking. The thermal characteristics of the system was tested under three conditions: charging, 24 hours of heat storage, and discharging. The author of the study concluded that sunflower oil is a suitable medium because of its high specific heat coefficient and moderate thermal conductivity. This research offered valuable information on the compatibility of sunflower oils for STES purposes, especially in residential settings.

Kajumba et al. [13] similarly designed a TES system, utilizing sunflower oil as both a storage material and a heat carrier fluid. Heat was transmitted by gravity from a thermal energy storage system through pipes to the base of the cooking pot, which was immersed in oil. The oil flow was controlled by a hand valve affixed to the line linking the cooking unit. It was also found that the heating rate and the cooking efficiency increased with the increase in the flow rate. The system was capable of boiling 2*l* of water in approximately 19 minutes at the maximum flow rate of 12 ml/s.

However, similar to other thermal oils, employing sunflower oil as the primary storage media in TES systems is associated with elevated expenses [56,66]. To reduce the expenses associated with exclusive oil usage, researchers have examined oil-packed bed TES systems which uses sunflower oil as a HTF.

An investigation conducted by Lugolole et al. [56] evaluated the efficacy of three STES systems: two packed-bed storage systems utilizing sunflower oil as the HTF with distinct pebble sizes (10.5 mm, 31.9 mm) and a system employing solely oil for storage. The results proved that the oil storage system charged more faster, second was the small pebbles, and lastly, the big pebbles TES because it had minimum thermal capacitance. The small pebbles TES exhibit a higher increasing temperature rate due to their superior capacity to reach thermal equilibrium, in contrast to larger pebbles that experience temperature drops. Three thermal performance metrics were assessed during charging cycles: stratification number, exergy rate, and energy rate. The small pebble system demonstrated superior charging energy and exergy rates, making it the ideal storage system for both energy and exergy rates, as well as all thermal performance characteristics evaluated [56]. The study indicated that thermal stratification in thermal energy storage systems utilizing liquid as a HTF enhances the energy performance of these storage systems.

2.2.3.1 Oil/rock bed TES systems

Oil/rock bed TES systems use aspects of thermal conductivity as well as heat-storing ability of rocks together with the storage ability of oil to produce a system that stores and releases thermal energy. In these systems, the selection of oil and rocks is strategic: oil serves as the HTF to facilitate thermal transfer from the charging point to the storage medium, while rocks serve as the principal storage medium owing to their substantial thermal mass and stability [23].

Oil serves as an effective thermal energy storage (TES) material, functioning well as both a thermal conduction and thermal retention medium at temperatures reaching around 230 °C, making it appropriate for cooking purposes [23]. This synergy is especially advantageous in solar thermal applications, where high-temperature storage and gentle heat release are critical. The fluid nature of oil guarantees even heat dispersion and promotes natural convection.

Rocks are chosen for their elevated specific heat capacity, density, and durability [67]. Moreover, rocks are abundant and readily accessible in several locations, are cost-effective, requiring only transportation to the site, exhibit both thermal and chemical stability across a broad temperature spectrum, and are non-toxic and non-flammable. They possess a high specific heat capacity, excellent thermal conductivity, a minimal coefficient of thermal expansion, and substantial mechanical resistance against thermal cycling, with all rocks having a melting point over 900 °C. Furthermore, pebbles function as both a heat conduction surface and a storage media, eliminating the necessity of a costly HTFs [70]. This dual process improves the TES system's capacity to store adequate energy for utilization during periods without sunlight, alleviating an important limitation of solar cooking systems.

Previous studies have significantly advanced the understanding of oil/rock systems, emphasizing design, material composition, and system performance. researchers in Uganda developed a TES system using a 45L storage tank integrated with a cooking compartment [23]. The authors experimented with two types of heat storage mediums: oil and oil-rock pebbles. The performance of the systems was analyzed in terms of the charging temperature, the heat retention capacity, the energy stored, efficiency, and the overall heat lost coefficient. The findings revealed that the oil-rock system had the highest efficiency of cooking with 64.9%, while the oil-only TES system had about 60%. Additional experiments on meal preparations showed that the system was capable of cooking beans in 2.25 hours with the oil-only TES and in 2.0 hours with the oil–rock pebbles TES system [23]. This research proved how efficient it is to use a combination of oil and rocks for storing heat for cooking.

Lugololе et al. [56], in their study comparing the performance of three STES systems of oil-pebble configuration, also supported the findings by stating that the oil/rock systems had a better heat storage capacity during the charging cycles due to the thermal mass of rocks and high heat transfer coefficient of the oil.

In addition, Sharoshoy, et al. [73] studied the effectiveness of a STES for cooking purposes. The system consisted of a cooking unit as well as a heat storage tank filled with Duratherm 630 oil and rock pebbles. Two tests were performed during charging and discharging. During charging, it required 2 hours and 50 minutes to cook beans and 160 minutes to boil 40 liters of water during discharge. The temperature that remained in the storage unit after the cooking and discharging procedure was 120 °C, which was deemed sufficient for preparing various types of food [73]. However, this system was said to be much expensive for household applications.

Therefore, the use of oil-rocks combination in TES systems has been found to be a reliable solution for coking processes. The empirical reviews continuously emphasize that the combination takes advantage of the strengths of both materials to offer high thermal efficiency and durability.

2.2.3.2 Research gaps and opportunities on oil/rock bed TES

There is a substantial research gap in Namibia regarding thermal energy storage technologies for solar appliances. Despite the demonstrated advancements in previous research, certain limitations impede the ubiquitous implementation of oil/rock bed TES systems, particularly in residential culinary applications. Majority of this research focused on large industrial systems, disregarding concerns such as rural residences or small-scale culinary techniques [73].

Additionally, the majority of advanced systems that are linked by pipelines need pumps to circulate the heat transfer fluid from the storage to the cooking units. The drawbacks of these system designs encompass elevated system costs attributable to the pump, thermal losses in the connecting pipes, and the risk of system failure if the pump malfunction. Nonetheless, certain systems become intricate owing to the existence of distinct containers or components, including heat storage, cooking units, charging/heating units, and pumps [13,23,56].

This study's design is innovative as it acknowledges and tackles the identified drawbacks. Namibian families may implement the sustainable alternative described in this study by using locally obtained and inexpensive sunflower cooking oil and easily available rock pebbles. The design's fundamental structure is an old water heating geyser, which facilitates recycling and reduces production costs. The use of aerolite insulation to reduce heat loss and natural convection as a heat transfer mechanism exemplifies the system's simplicity and efficacy. Consequently, it is suitable for rural applications.

This work addressed these deficiencies by creating a compact heat-storage system for residential use that incorporates all necessary components in a single enclosure. The technology allows users to cook while heating or charging, and it also stores heat for future use or nighttime applications. Furthermore, the developed system is scaled down to accommodate all the required elements in a single enclosure and optimized for residential application.

This current study is based on the principles outlined by Nydal [71] and forms part of the research being conducted in Uganda and at NTNU in Norway [23,72,73].

2.3 Heating the TES system with PV panels versus a Solar concentrator

There are several ways of charging a TES system, especially for cooking, including the use of PV systems or solar concentrators [16,17]. Each method varies in its operation, effectiveness, and drawbacks.

PV systems operate by converting sunlight into electricity, which then powers resistive heaters and charges the TES system [15,16,17]. The efficiency of PV panels varies depending on their type; monocrystalline panels typically exhibit an efficiency of 15%-22%, whereas polycrystalline panels demonstrate an efficiency of 13%-18%. These systems offer advantages such as their versatility in applications beyond heating and their expansion through the addition of more panels, particularly for existing PV systems [21,22]. However, PV systems may experience energy conversion losses (from sunlight to electricity to heat) that will result in the TES system's efficiency loss [71]. On the other hand, solar concentrators focus solar thermal energy onto a receiver, directly heating a fluid or medium that subsequently transfers heat to the thermal energy storage system

[15,74]. These systems can operate at higher overall efficiencies because of direct heat transfer [74].

Additional benefits of these systems include their capability to attain high temperatures appropriate for diverse thermal applications, and they eliminate the number of energy conversion stages, which may enhance the efficiency of the TES system. However, these systems need tracking mechanisms to keep the focus on the sun and may be mechanically complex compared to PV panels [14,71,74], making them difficult to install and maintain.

Although PV systems have low conversion efficiency for sunlight to electricity, the solar concentrators can attain high thermal efficiencies because of direct heat collection. Solar concentrators are better suited for direct heat applications like water heating or industrial applications, while PV systems, when combined with resistive heating, can serve both electrical and thermal purposes [14,15,16,17]. Concentrator systems may necessitate more complex structures, such as tracking structures, compared to the simpler structures needed to mount the PV panels.

Mawire et al. [74] conducted a practical comparison between a DC PV cooker and a parabolic dish solar cooker under different non-ideal solar radiation circumstances. The experiments revealed that the input electrical power of PV cooker remained nearly constant at 160-180W, while the parabolic cooker's input thermal power varied greatly (200-1200W) based on the intensity of solar radiation. The thermal output capacities of the PV cooker (66-100W) were in the range of the parabolic dish cooker (78-142) even though its input power was very low. The ambient solar radiation and wind speed significantly influenced the efficiency of boiling water in the parabolic cooker. These experiments revealed that the PV cooker functions effectively in all weather conditions.

As postulated in this literature, this study therefore is proposing the use of a PV system to heat the developed TES system. The PV system appears to be more realistic and implementable for domestic use as compared to solar concentrators. As the cost of PV panel continues to reduce, these systems promise an affordable solution enabling easy deployment and expansion [17,20].

2.4 Arduino-based data loggers

In the last decade, Arduino-based data loggers have attracted much interest as they are customizable, flexible, and cheap. Such systems have been incorporated into different sectors such as environmental monitoring, solar energy systems, and agricultural applications. This section is focused on the key development and applications of data loggers based on Arduino boards, with the indication of the boards used and the purposes they have.

2.4.1 Arduino-based data loggers for environmental monitoring

Temperature, humidity and pressure are among the most common parameters that are monitored through Arduino-based data loggers, particularly in environmental applications. For example, an Arduino-based Cave Pearl data logger was constructed to serve as a multi-purpose monitoring platform [43]. This system used an Arduino Uno board, which is very reliable and can work with different types of sensors; it was used to record the changes in cave conditions such as drip rates and water flow in a flooded cave. The design flexibility was also given much importance, so that the researchers could easily change the system as per different environmental requirements and for different types of sensors.

Furthermore, a data logger system with a sole purpose of measuring humidity and temperature using an Arduino Uno board and a DHT11 sensor was developed [75]. This system also used a DS3231 real-time clock to time-stamp the data, the LCD display for displaying real-time data, and a piezo buzzer as an alarming system. The study was motivated by the urgent requirement to create a system that can monitor temperature and humidity in one system, with real-time data logging capacity and an inbuilt alarming system that would warn the user each time the predetermined temperature and humidity limits were exceeded. This work established the feasibility of using Arduino Uno boards in real-time measurement of environmental conditions.

In a similar study, a cost-effective, multi-sensor Arduino based system was built to monitor the dynamics of stream headwater catchments in mountainous regions [76]. The system developed utilized an Arduino Pro Mini board together with combined multi-sensors to measure factors such as water depth and temperature, demonstrating the versatility of Arduino platforms for multi- parameter environmental sensing. In the field tests, the researchers discovered that the monitoring system was power efficient; it was powered by four AA batteries and ran for nine months at a five-minute logging interval. The used Arduino Pro Mini board has similar pins to the Arduino Uno board which is reported to have a higher number of input/output pins. This was convenient because it allowed multiple sensors to be incorporated and offer an extensive array of data regarding the environment.

2.4.2 Arduino-based data loggers in energy systems

Another promising area of research is the application of Arduino data loggers in energy systems. They are used to control and manage energy systems. For instance, an Arduino-based data logger was designed to measure photovoltaic (PV) systems' parameters [42]. This system was meant to capture values like current and voltage generated by the solar panels. The system employed an Arduino Mega board. This study illustrated how such a system could be efficiently utilized in observing and enhancing the performance of PV systems, thus making it a useful tool in the utilization of solar energy.

Building on this, another study [44] developed an Arduino-based solar power parameter measurement device equipped with an integrated data recorder. This system incorporated an Arduino Uno R3 board; this is because it has the processing capability and memory to support several sensors besides its ability to record data for long durations. It was developed to measure the amount of solar irradiance, the panel temperature, current and voltage, as well as the atmospheric pressure. The developed device's validity was confirmed by comparing the measured parameters with established measuring devices, which exhibited close agreement.

In addition, a multichannel data logger using Arduino Uno for thermal measurement in solar still system was developed [37]. This system was able to record temperature data from several different locations within the solar still, giving a more accurate picture of the thermal process occurring. This application brought out the flexibility of Arduino platforms in handling thermal systems of high complexities.

Furthermore, a data logger was developed to measure thermal conductivity of building materials using Arduino Uno [39]. This study primarily focused on the system's performance regarding temperature recording, as temperature changes are crucial for assessing the efficacy of TES materials. Arduino Uno was chosen because it is simple and has enough computing power for thermal measurements required in experimental thermal energy research.

2.4.3 Arduino-based data loggers in Agriculture

Arduino based data loggers have also been used in agriculture especially monitoring of environmental conditions that influence crop production. In Turkey, an Arduino based low-cost data logger system was developed to record air temperature, humidity and air pressure in an agricultural environment [40]. The study employed an Arduino uno R3 board to record the environmental factors that are essential in enhancing irrigation and other practices in agriculture. The system was exposed to outdoor conditions for one week in the spring and one week in the summer and it was discovered that the system was capable of collecting data at one-hour intervals. Such cost effective and adaptable instruments were underscored by this study as crucial for improvement of yield in the field of agriculture particularly in the developing world.

In contrast, a study explored the feasibility of using Arduino data loggers in the irrigation systems [77]. Their design was specifically devoted to the assessment of in-canopy sprinklers installed in center pivot irrigation systems. The goal was to design a monitoring system for in-canopy sprinklers used in center pivot irrigation which was capable of identifying the correct location and time of an in-canopy sprinkler separation from the center pivot span. The Arduino Uno board was employed and also the Arduino MKR GSM 1400 board was selected due to the fact that this board has built-in 3G cellular compatible modem. This made it easier for the microcontroller to enable and disable the sending and receiving of the SMS text messages through the Arduino MKRGSM library. This board also encompasses greater flash and dynamic memory as compared with the

Arduino Uno. This application depicted how possible it is to design data loggers using Arduino, that suit the needs of agriculture, through providing real-time data that would help in proper usage of water and management of crops.

In conclusion, the analyzed works as a whole reflect the flexibility and efficiency of Arduino-based data loggers for different contexts, ranging from the environmental to the solar energy to agricultural applications. The choice of Arduino board is based on the number of sensors that are needed as well as the complexity of the data processing that is required and the need for data logging. Besides, these systems do not only point to a cheaper means of data collection but also enable the flexibility that can be required especially when working in different conditions and with varying goals and aims. As research on these fields' advances, Arduino-based data loggers will remain very useful tools in acquiring precise and thorough data that will fuel development of renewable energy, environmental discipline and agriculture.

Chapter 3: Research methods

3.1 Research design

This study utilized a quantitative, experimental design. The data was collected with temperature sensors connected to an Arduino data logger, discussed in section **3.2.2.** The workflow for this study is summarized below.

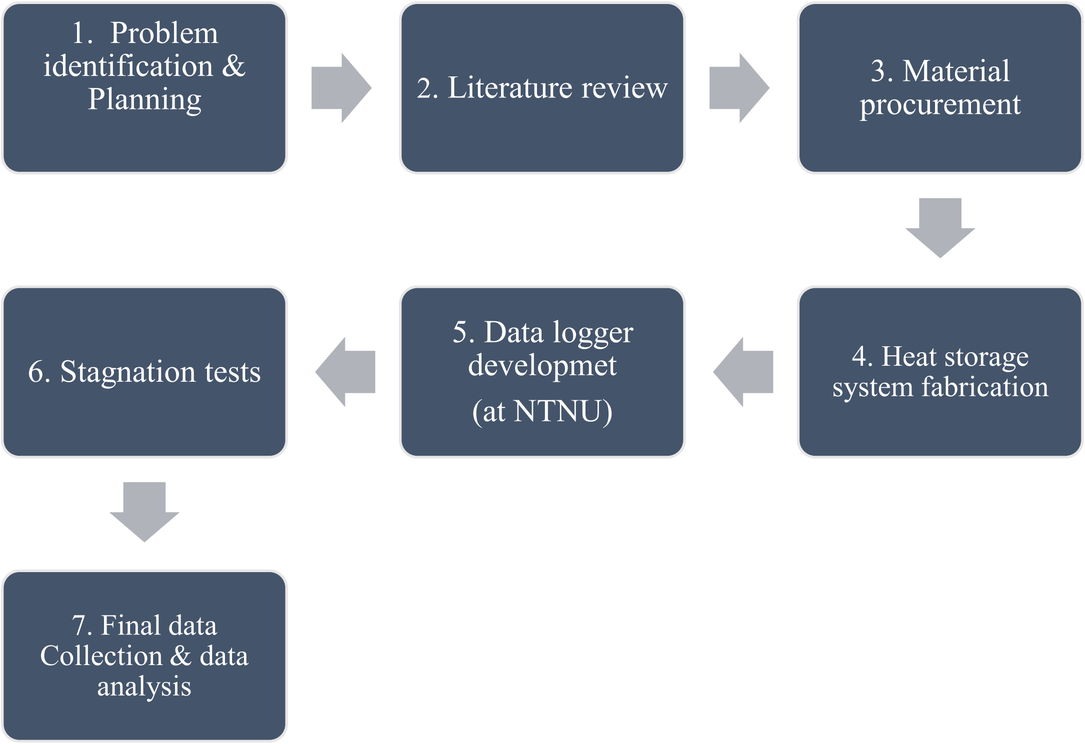


Figure 5: *Study workflow*

3.2 Data collection procedures

3.2.1 Design and development of the oil-rock bed heat storage system

Existing thermal energy storage systems were reviewed. The specifications for the design for the current study was then developed in response to the identified gaps from the literature. The design was developed based on locally available materials and the chosen sensible heat materials (Sunflower cooking oil and rock pebbles).

The system was designed using a locally procured cooking pots and an old water heating geyser that housed all the components. It has three coaxial cylinders in addition to the outer cylinder which is the water geyser. The geyser has a width of 47cm and height of 60 cm, the second cylinder was a pot of diameter 26cm and height of 25cm and the third cylinder is another pot of diameter 18.8cm and height of 14cm. The inner cylinder is a pot of diameter 15.5cm and height of 12cm, this act as a hot plate where the pot was placed during cooking. The geyser was made of iron steel of thickness of about 2mm while the three pots were made of Aluminum plate of thickness of about 0.5mm.

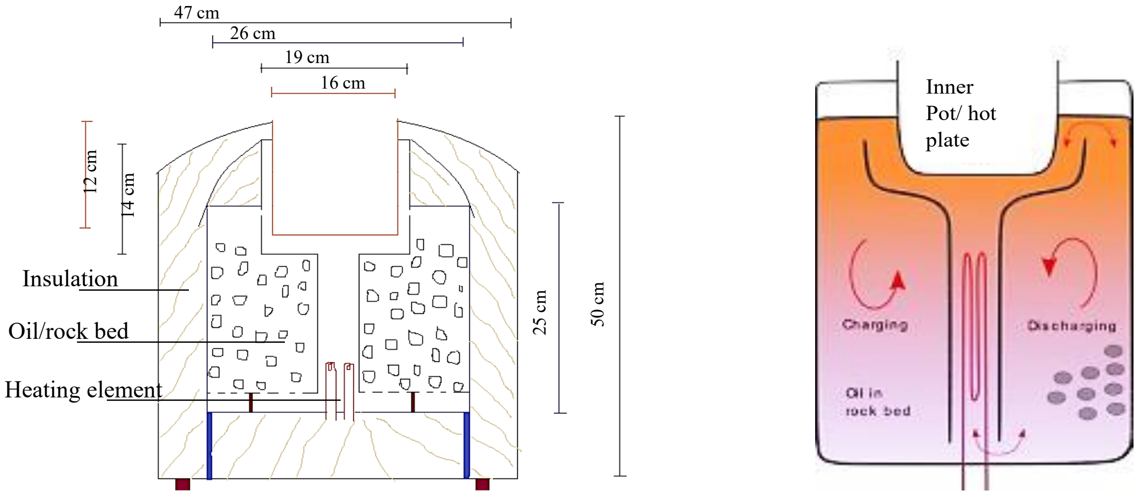
The space between the geyser and the second cylinder (pot) as well as the space between the cover lid and the inner cylinder will be filled with Aerolite Soft Touch ‘Glasswool’ insulation, to minimize heat loss. Two small circular holes of diameter of approximately 0.5cm each, were drilled on each side of the third cylinder, this allowed the flow/expansion of the oil when it started to heat up. The heat in the system was being transferred through natural convection between the cooking pot and heat storage, due to the density differences of hot and cold oil.

The heat was transferred when the hot oil expands and flow through the pipe attached to the perforated plate at the bottom of the inner cylinder which was in contact with the pot, and down via the two expansion holes to the rock-oil bed, forming a circular motion. The lid of the geyser cylinder had a small hole on top to allow the wires to the heating elements to pass through as well as the thermocouples. A 12V heating element was fixed at the bottom of the second cylinder (this is the element which heated the system) – they initially were two but one malfunctioned mid experiment and could not be replaced.

Figure 6: *The fabricated TES system*

Figure 6 shows the various parts of the fabricated TES: with (a) 12V element (b) storage cylinder in geyser container (c) perforated plate + circulation pipe + oil cylinder (d) all components (e) storage system in insulation (f) complete insulated system (g) whole closed system (h) TES system + data logger (i) washed pebbles.

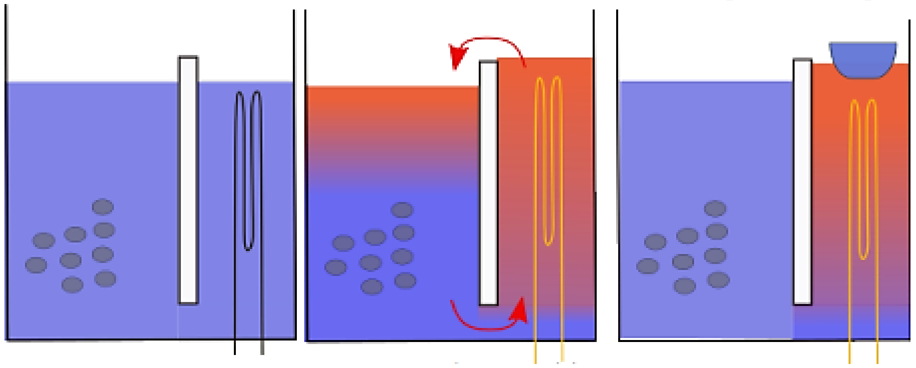
The schematic diagrams of the designed system are shown below, including the illustrations of the internal oil circulation processes when the system is not being heated, heated with no cooking taking place, heated while also cooking and cooking on the heat stored in the system alone:



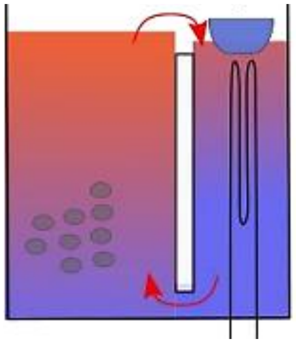
Cold system, no power/heat

(Heating, no cooking) oil overflow through the holes of inner pot due to expansion

(Heating, no cooking) oil overflow through the holes of inner pot due to expansion



(Heating, no cooking) oil overflow through the holes of inner pot due to expansion



Credit: Prof. Ole J. Nydal, NTNU

Figure 7: *Schematic diagrams of the developed heat storage system*

3.2.2 Development of the Arduino data logger

3.2.2.1 Materials used

In this project, an Arduino data logger was built using an Arduino-UNO R3 board and Type-K temperature sensors. In addition, a current sensor and voltage regulator was used for additional, possible measurements with a PV panel. **Figure 8** indicates a block diagram of the built data logger with four temperature sensors interfaced between the heat storage system and the Arduino board, RTC Module, SD Card, LCD display and a laptop or power supply. The data obtained from sensors were analog; thus, conversion to a digital counterpart was executed using the Arduino UNO's analog-to-digital converter module written in C language.

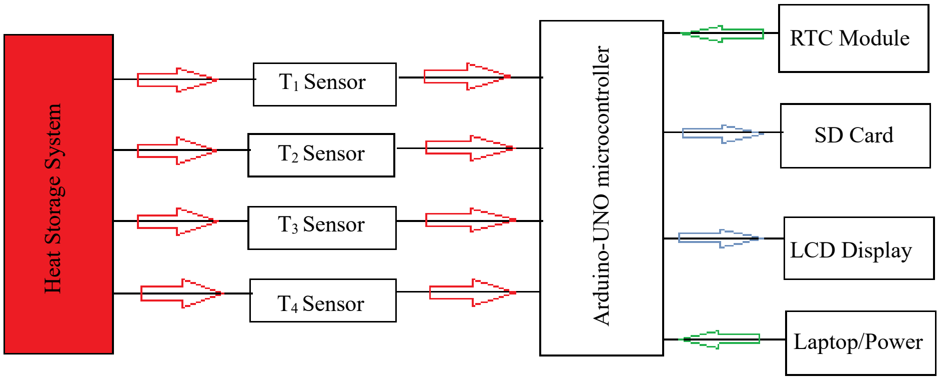


Figure 8: *Block diagram of the built Arduino-Uno data logger and connections from the TES*

3.2.2.1.1 Components used

3.2.2.1.1.1 Arduino UNO R3 board

The Arduino UNO R3 is a circuit board utilizing the ATmega328P microcontroller [36]. The ATmega328P functions as the central processing unit of the data logger, managing all components and processing data from the sensors. **Figure 9** illustrates the board, which features 14 digital input/output (I/O) ports that may interface with additional expansion boards (shields) and other circuits. Six (6) digital pins are capable of functioning as Pulse Width Modulation (PWM) outputs. The board further has six analog inputs, a 16 MHz crystal oscillator, a USB connection functioning as both a power supply and communication interface, a power connector, an ICSP header, and a reset button [36,44].

The board is programmable using the Arduino IDE (Integrated Development Environment) through a type B USB connector. The IDE program is free to download from the Arduino software webpage [78] , depending on the operating system of the user. The board may be powered via a USB connection or an external 9-volt battery, accepting voltages ranging from 7 to 20 volts [75]. The ATmega328P on the board is preloaded with a bootloader that enables the uploading of new code without the need for an external hardware programmer [75]. The primary attributes of the Arduino Uno R3 microcontroller are presented in **Table 1** [36,39] and the board with the labelled parts is shown in **Figure 9** below.

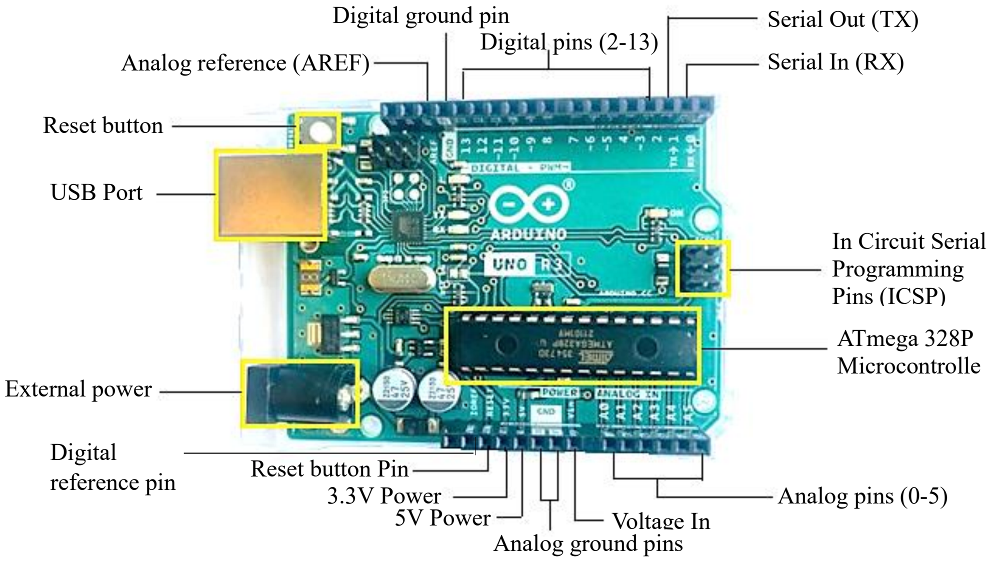


Figure 9: *Arduino-Uno R3 board*

All 14 digital pins on the Arduino Uno board may function as either inputs or outputs, employing the pinMode(), digitalWrite(), and digitalRead() methods. All operate at 5V. Each pin may provide or receive a maximum of 40 mA and is equipped with an inbuilt pull-up resistor with a range of 20 to 50 kΩ, which is deactivated by default. Furthermore, certain pins possess specialized capabilities, as indicated below [36]:

i. Serial: 0 (Receive) and 1 (Transmit). Facilitates the reception (RX) and transmission (TX) of TTL serial data. The pins are linked to the respective pins of the ATmega8U2 USB-to-TTL Serial chip.
ii. External Interrupts: 2 and 3. These pins can be configured to trigger an interrupt upon a low value, a rising edge, a falling edge, or a change in value.
iii. PWM: 3, 5, 6, 9, 10, and 11. Employ the analogWrite() function to produce 8-bit PWM output.
iv. SPI: 10 (Slave Select), 11 (Master Out Slave In), 12 (Master In Slave Out), 13 (Serial Clock). These pins provide connection for the Serial Peripheral Interface (SPI) bus via the SPI library.
v. LED: 13. An integrated LED is linked to digital pin 13. When the pin is at a HIGH state, the LED is activated; when the pin is at a LOW state, it is deactivated.

Furthermore, the board possesses 6 analog inputs, labeled A0 to A5, each offering 10 bits of resolution (i.e., 1024 distinct values). By default, these inputs can measure from ground to 5 Volts; however, the top limit of their range may be adjusted using the AREF pin and the AnalogReference() function.

Besides digital inputs, several pins offer distinct functions:

vi. TWI: A4 (SDA) or A5 (SCL) pin. Enable TWI communication using the Wire library. The remaining pins on the board consist of:

vii. AREF. Reference voltage for analog inputs. Employed alongside analogReference().

viii. Reset. Links a LOW line to reset the microcontroller, frequently utilized to include a reset button on shields that impede access to the board's reset button [36].

Technical details of an Arduino UNO board are presented in **Table 1** below [36,39].

Table 1: Technical details of an Arduino UNO board

Microcontroller	ATmega328P
Operating Voltage	5V
Input Voltage	7-9V
Input Voltage (limits)	6-20V
Digital Input/Output (I/O) Pins	14 (6 provide PWM output)
Analog Input Pins	6 (No output pins)
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328P) (0.5 KB used by bootloader)
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock/processor Speed	16 MHz
Serial communication protocols	UART – I^2C –SPI
Analog-Digital Converter (ADC)	10 [bit]

3.2.2.1.1.2 Data logging shield

This is an add-on board that is used to do the data logging functions. It provides functionalities such as the SD card interface for the storage of data and a Real-Time Clock (RTC) to time stamp data.

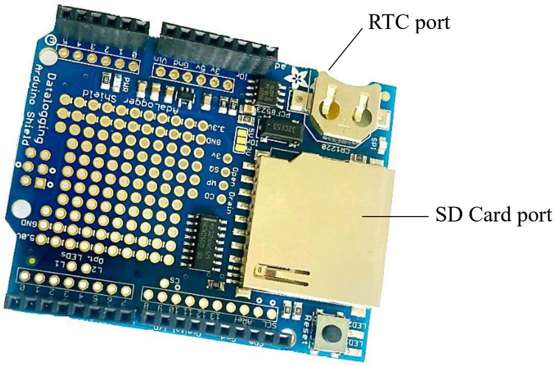


***Figure 10**: Data logging shield*

The shield provides the following features/functionalities [41]:

a) Able to use any SD card with a FAT16 or FAT32format. The 3.3V level shifter circuit enables fast data reading and writing, and prevents damages on SD Card.

b) The RTC ensures that the time will still be ongoing even when the Arduino board is not connected to a power source.

c) A 3.3V voltage on-board regulator can be used as the reference potential (Vref) and to power up the SD card that needs a lot of power to work. This is needed in case one uses a PV system for instance.

d) It uses an “R3 layout” for Inter-Integrated Circuit (I^2C) bus dan ICSP SPI ports, so it will suit many types of Arduino boards

3.2.2.1.1.3 Bi-directional level shifter

A device used to safely interface different voltage levels between components. Here, it is used to interface the voltage between the Arduino (5V logic) and the thermocouple amplifiers (3.3V logic). The level shifter is the connection between the Arduino and the amplifiers for the thermocouples, and enables them to have a single data line in to the Arduino.

Since the Arduino R3 board uses a 5 V logic and the amplifiers use the 3.3 V, all wires connecting the board to the Inter-Integrated Circuit (I^2C) bus needed to pass through a bi-direction logic level converter. This converter steps down all outgoing 5V signals to 3.3V while simultaneously stepping up incoming 3.3V signals to 5V. To accomplish this, it requires voltage inputs of 5 V and 3.3 V [77]. The bi-directional is shown in **Figure 11** [79].

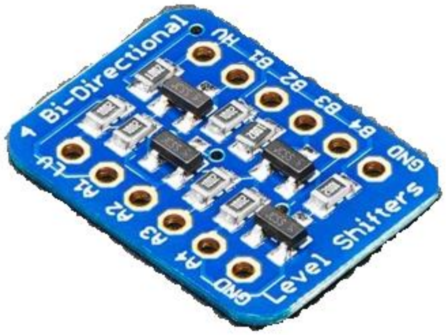


Figure 11: *Bi-directional level shifter*

The level shifter has a low voltage side (on the left 'A1-LV') and high voltage side (on the right 'B1-HV') as seen in Figure 4. Since the level shifter works on the I^2C communication bus, there is only a need of one data line (SDA) to the amplifiers in addition to ground and power.

3.2.2.1.1.4 Max31850 Type-K Amplifier

Thermocouples are very low-level signals and often require amplification or a high-resolution transducer to process the signals, and since the signal is analog, an analog-digital converter must be present to convert these analog signals into digital signals that are compatible with the Arduino inputs [44]. The amplifiers condition the small voltage output from the thermocouples, amplifying it to a level that can be read by the Arduino.

The amplifiers include a 2-pin terminal block for thermocouple connection, a 4.7kΩ data line pullup resistor, and a pin header for breadboard or perfboard connectivity [80].see **Figure 12** below [81].

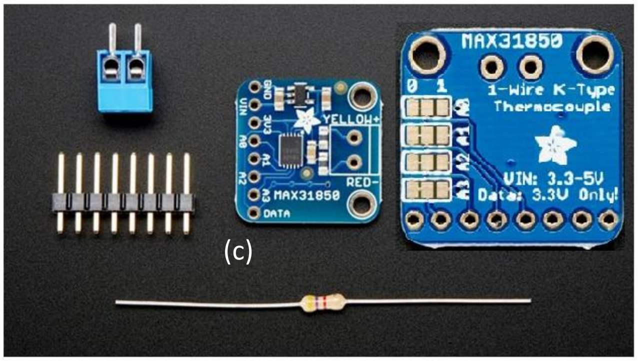


Figure 12: *Max31850 Amplifier a) Front look b) Back look c) Terminal block d) pin header e) Resistor*

Table 2: Features of Max31850 Amplifiers

	Features
1.	Only work with K-type thermocouple (Any)
2.	-270°C to +1370°C output in 0.25 degree increments
3.	Internal temperature reading
4.	3.3 to 5v power supply - Data line is 3V only
5.	1-Wire interface allows any number of thermocouple amps on a single data line

3.2.2.1.1.4.1 Resistor

The resistor (shown in **Figure 12**) is used as a single data line between the level shifter and the amplifiers to limit the current flow and protect the components (such as SD Card) from damage.

3.2.2.1.1.5 Type-K Thermocouples

These are sensors that measure temperature. They produce a voltage proportional to the temperature difference between two junctions. The type-K thermocouple detects variations in room temperature and transmits an electrical signal to the amplifier, which amplifies the signal and communicates it to the Arduino [82].

3.2.2.1.1.6 LCD Shield

A display module that shows real-time data, system status and other information. It allows users to monitor the temperature and other data directly on the device, without having to have a pc/laptop open. The LCD shield is equipped with five programmable buttons as seen at the bottom left of **Figure 13** (researcher's taken photo), a reset button and a display adjustment rheostat (Orange button) on the bottom right. This shield also works on the I^2C communication bus.

Figure 13: *LCD Shield*

The LCD buttons were programed as shown in **Table 3** below. To change the functionalities of these buttons, changes need to be made to the Arduino IDE program/codes in Appendix A. **NB:** The buttons need to be pressed for about a second in order to activate.

Table 3: The LCD buttons and their programmed functions

Button	**Function**
Left	File number readout
Up	Date and log number readout display
Down	Current, Voltage & Power readout display
Right	Turns off display/screen
Select	To show the 4 temperature readings
Orange	LCD adjustment
Reset	Resets the Arduino and starts the program from the beginning

3.2.2.1.1.7 SD Card

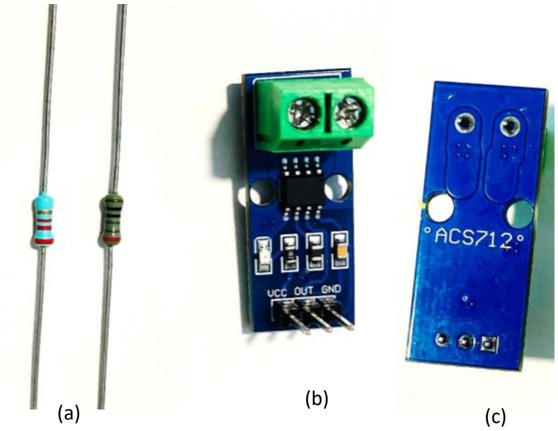
The SD card is used to store the temperature readings (or other data) recorded by the data logger over time. Upon receiving the signals, the Arduino will transform them into data, which will be recorded into the SD Card in a **.txt** file format, accessible via spreadsheet applications such as Microsoft Excel [41]. A 16GB card was used to store all data received from sensors.

3.2.2.1.1.8 Real-Time Clock (RTC)

The RTC observes the present time, enabling the data logger to precisely timestamp each recorded data point. The RTC provides the capability to maintain the current time even while the microcontroller is inactive. The real-time clock is powered by a specific battery that is independent of the power supply. Consequently, the date and time for each data entry will remain unaffected when power is disconnected from the circuit [35]. The RTC operates on a 3V lithium coin cell battery, ensuring continuous functionality even when the shield is not powered.

3.2.2.1.1.9 Voltage divider and shunt

In the case where the heat storage system is being heated with a PV panel, a voltage divider and shunt are needed. This is because the PV panel produces a varying voltage due to the variations in solar variation throughout the day. Hence, the Arduino will not be able to use this power directly. A converter is required to create a consistent 5 V from the electricity produced by the PV panel for the Arduino's power input. This voltage converter will need a positive and negative input of power from the PV panel. To enable the Arduino to measure the voltage and current generated by the PV system powering the heating elements, a shunt is required. This shunt is for current measurements.



(a)
(b)
(c)

Figure 14: *The resistors for voltage divider (a) and current sensor (b) front (c) back*

The shunt/current sensor has a built-in ACS712 sensor, these sensors use the Hall effect principle to measure current [83]. The current moving through the shunt creates a magnetic field which then is translated to a proportional voltage in the integrated circuit of the sensor. The 2-pin terminal block is soldered to the board and the wires of the external circuit is fastened to this block. To send this information to the Arduino, there are three header pins: VCC, OUT and GND. VCC and GND are for power and ground connection respectively, while OUT is the data line. The ACS712 sensor used has a capacity at 30 amperes and a sensitivity of 66 mV/A.

The solar PV voltage is measured by employing a voltage divider, which is a simple circuit that reduces the voltage of the PV panel to a level that can be safely measured by the Arduino. The voltage divider principle implies that: when two resistors are connected in series across a voltage source, the voltage drop across each resistor is directly proportional to its resistance. The voltage divider takes advantage of this property to "divide" the input voltage into smaller, measurable voltages.

The current sensor interface circuit consisted of two series resistors R1 and R2 with values of 2.2kΩ and 1kΩ, respectively. This could allow an input voltage of up to 16V. In the case of input voltages greater than 16V, several other resistor combinations were added (680Ω & 3.3 kΩ; 330Ω & 3.3 kΩ; 330Ω & 5.1 kΩ) to measure voltages of up to 29V, 55V and 80V respectively. These resistor options were made in such a way that the resulting current does not exceed the accepted/safe value for the Arduino. The highest permissible current for the atMega328 Arduino is 200 mA in total across all pins, with a limit of 20 mA per individual I/O pin [84].

The resistance factor (Rf), derived from equation **(9)** , is responsible for converting the voltage back to the original solar panel value for display on the PC and LCD shield. The output voltage of the solar panel is specified by equation **(** 8) [44].

The voltage scaled factor (voltage at the divider junction) is given by:

$$V_f = \frac{R_1 + R_2}{R_1} \tag{7}$$

Where, R_1 is the smaller resistor (closest to the ground) and R_2 is the bigger resistor (closest to the input voltage)

$$Measured\ Voltage = \frac{Voltage\ divider\ analog\ value + Reference\ voltage\ (5V\ for\ arduino)}{Resistance\ factor\ (R_f)} \tag{8}$$

$$R_f = \frac{1023}{R_1/(R_1+R_2)} \tag{9}$$

The solar panel current is quantified using equation **(** 10) [3] whereas the power is calculated using equation **(** 11).

$$Measured\ current = \frac{(Analogue\ value \times Analogue\ factor) - AC\ offset}{Sensitivity} \tag{10}$$

In this context: Analogue factor = 5/1023, AC offset = 2500mA, and Sensitivity = 66mV/A

The output of the PV panel was computed as:

$$Power = Measured\ voltage \times Measured\ current \tag{11}$$

3.2.2.1.1.10 Solar charger shield and Voltage regulator

In addition, a solar charger shield and voltage regulator were added. The solar charger shield is a power system, capable of accepting power from solar cells, and via micro-USB. It is used to charge a Lithium-Ion battery which will provide power to the Arduino when no other power source is connected and it will be charged when external power is available. The battery used in this study is a LiFe 3.7V and 1 200 mAh. This solar shield is suitable for field work, in cases where no electrical power connection is available, the data logger can run on this battery while at the same time being charged by a small PV panel. It is shown in **Figure 15** [85].

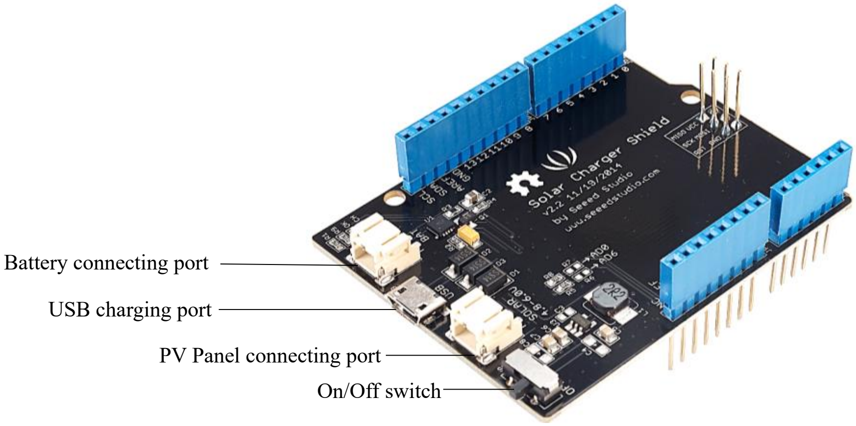


Figure 15: *Solar charger shield*

Figure 15 shows the Solar charger. The shield has an on/off switch. If this switch is turned on, the battery and PV panel will be powering the Arduino, and if it is off the Arduino must be connected to an external power through the USB port to stay on. In the case where the Arduino is connected to power through either of the ports and the switch is on the battery will be charging.

In the case where the Arduino is being charged with PV panel of voltage greater than 5V, a voltage regulator will be needed to ensure that no matter the input of the PV panel used, the output will always be 5V (suitable for the Arduino). An LM2596S DC-DC Adjustable Voltage Power Module, from [86] , was chosen in this study (although will not be used). It takes the input power from the PV panel and send out a stable 5 V feed to the Arduino input port.

Figure 16: *DC-DC Voltage regulator*

3.2.2.2 Soldering and pin configuration

Soldering is a technique frequently employed in electronics that utilizes a filler metal with a low melting point, referred to as solder, to connect metal surfaces. The solder typically comprises an alloy of tin and lead, with melting points of around 235°C and 350°C, respectively. The alloy is melted using a soldering gun at temperatures above 316 °C. Upon cooling, the solder forms a strong electrical and mechanical link between the metallic surfaces. This bond enables the metal components to establish electrical contact while being secured in their position [82]. Please see [87,88] for a step-by-step guide on soldering.

In this project, soldering was done only for the data logging shield, level shifter and the amplifiers as the other components (Arduino board and LCD shield) were already soldered.

3.2.2.2.1 Data logging shield

The first step to soldering the data logging shield is getting the right (sized) stacking headers and soldering them on the shield as shown in **Figure 17**. Stacking headers were used in order to allow the stacking of other shields (e.q LCD shield) on top of the data logging shield.

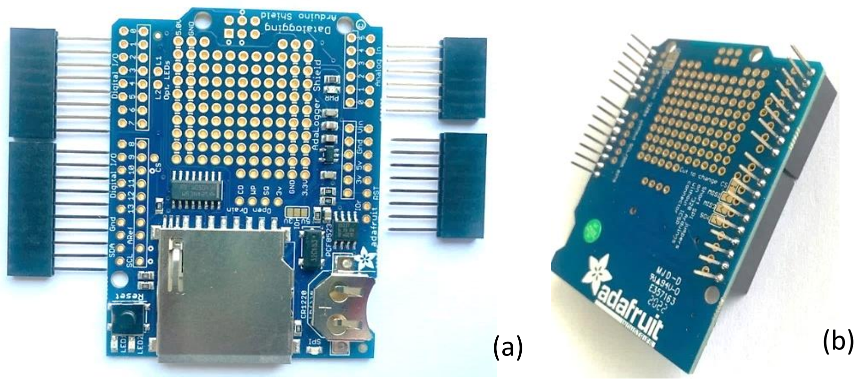


Figure 17: *Data logging shield (a) before and (b) after soldering*

3.2.2.2.1.1 Level shifter

The second step of soldering the logging shield was adding the level shifter. The wires that connect the level shifter to the data logging shield need to be soldered on the level shifter before soldering it to the data logging shield. It would be best if different color-coded wires could be used for the different pins, for easy identification. In this work, a single color ‘yellow’ was used as those were the only wires available and appropriate for soldering on the level shifter as shown in **Figure 18**.

On the low voltage side LV (first, top-left) is connected to the 3.3 V of the data logging shield. A1 (second, top-left) is connected to the 4.7 kΩ resistor, which also goes to the 3.3 V. On the side of high voltage, HV (first, top-right) was connected to 5.0 V on the data logging shield while, B1 (second, top-right) is connected to one of the of 14 digital inputs. B1 is for the data line to the Arduino. According to the Arduino IDE program that was used in this project, this need to be connected to pin 2. If a different pin is desirable, then the program needs to be changed as well. Ground (bottom wire) on both sides go to the ground of the data logging shield.

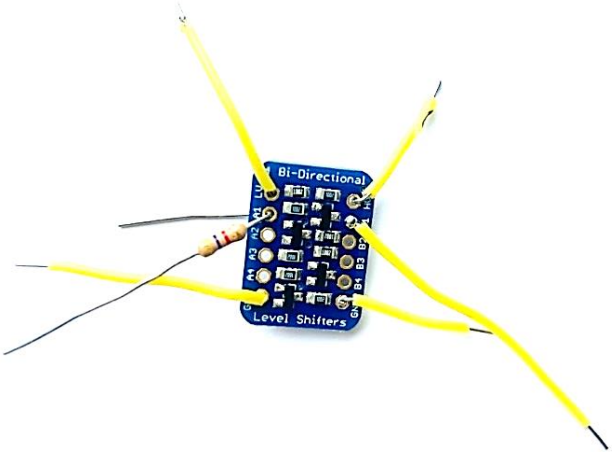


Figure 18: *The level shifter after soldering*

After soldering the wires to the level shifter, it is then soldered on the data logging shield according to the descriptions given above, under section **3.2.2.2.1.1**. In order to prevent a short circuit, after soldering the wires to the level shifter, all the wires (**Except the resistor**) need to be cut as short as possible. The resistor needs to be long enough, so that it can pass through the hole on the logging shield to the other side. The resistor needs to first be soldered on the data logging shield, with the send side passing through the hole to the other side and then soldering of the rest of the wires follows.

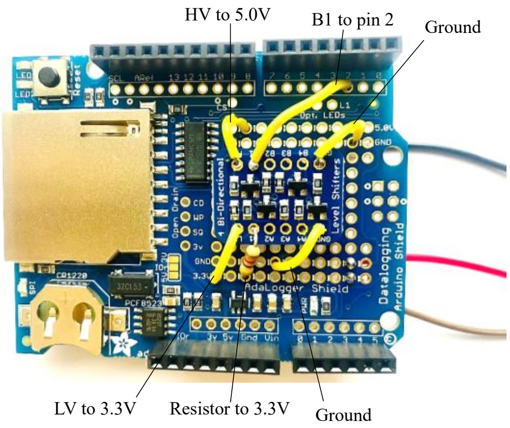


Figure 19: *Data logging shield with the Bi-directional level shifter*

The resistor is used as a data line from the amplifiers and it is the black wire in **Figure 19** and **Figure 20**. In **Figure 20**, the Brown wire is 3.3 V power line to the amplifiers, while the red wire is for ground.

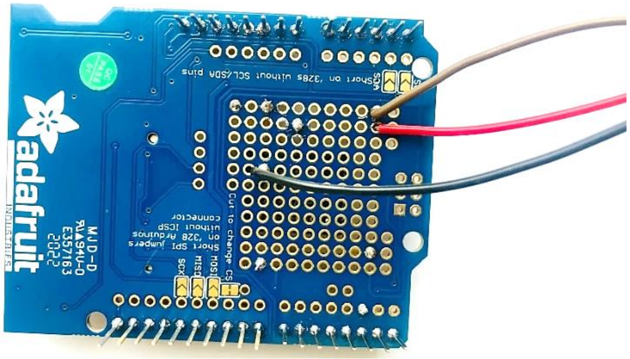


Figure 20: *Back side of the data logging shield with the level shifter*

3.2.2.2.2 Max31850 Amplifiers

The amplifiers (as shown in **Figure 21**) are mounted on a stripboard, this enables all the four amplifiers to send data to the same line output, as long as they are connected in the same way and on the same lines on the stripboard. The stripboard mounting makes it easy for a connection of only three (3) wires between it and the Arduino: Ground, power and a data line. The amplifier is connected to the stripboard using header pins and an extra header pin is mounted at the top of the amplifiers on the stripboard for the connection of the three wires to the Arduino.

The orientation of the amplifier is important as one need to know which header pin is needed for ground, power and data line. In addition, one need to confirm that the correct terminals (+ve and -ve) of the 2-pin terminal block is connected/soldered correctly to the amplifiers, this will ensure a correct connection to the thermocouple sockets. In **Figure 21**, some amplifiers are connected front-side down (See **Figure 12** (b)) on the stripboard.

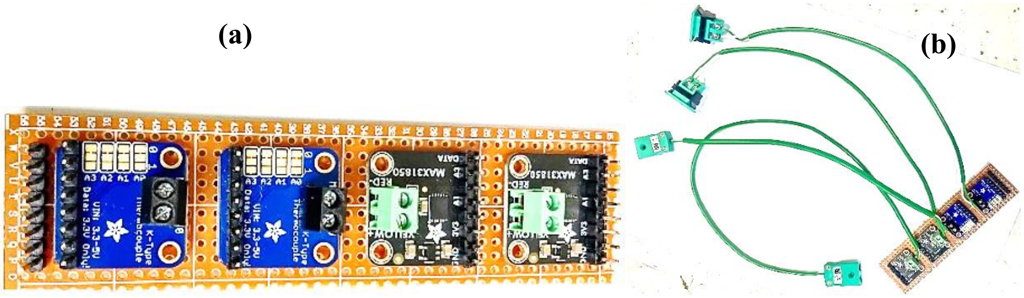


Figure 21: *The four amplifiers a) on the Stripboard, b) connected to type-K thermocouple sockets*

3.2.2.2.3 Shunt and voltage divider interface

The final part of soldering was for the current sensor interface circuit (voltage divider and shunt) onto a stripboard as shown in **Figure 22**.

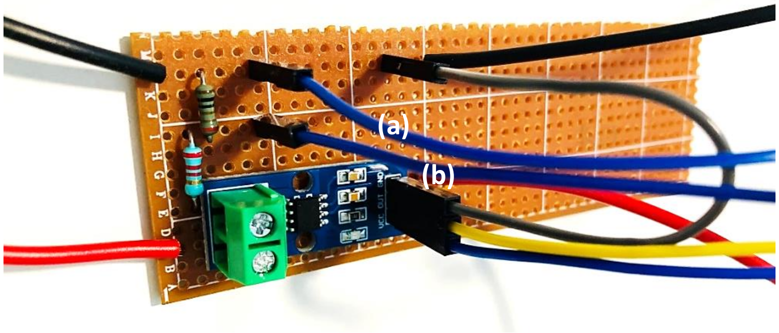


***Figure 22:** The current sensor and voltage divider interface*

In **Figure 22**, the wires connected to the current sensor's three pins (VCC-Blue, Out-Yellow and GND-Grey) are color coded. The Yellow wire will connect to pin 2 on the Arduino (for current measurement), the blue wire will be connected to the analog pin 5V (data line) and Grey is for ground connection. Moving to the top (the two blue wires) a) is for ground connection while b) is for voltage measurement from the voltage divider. The two thick wires (red, +ve and black, -ve) are for connections to the power source (PV panel). Likewise, the two thick (black and red) wires at the back are for connections to the heat storage system (heating elements).

3.2.2.2.4 The complete data logger

The four shields (Arduino board, Data logging shield, Solar charging shield and the LCD shield) are stacked together to make an Arduino stack, while the other components are either connected to the shields or the Arduino to make up the total system as seen in **Figure 23** below and all components were well arranged in a box with some small openings to allow connections to the heat storage system. The USB cable (black in cable in bottom right picture) is used for connecting the Arduino to a laptop (or Power bank), where it can get power and the program that is written can be downloaded and stored on the device.

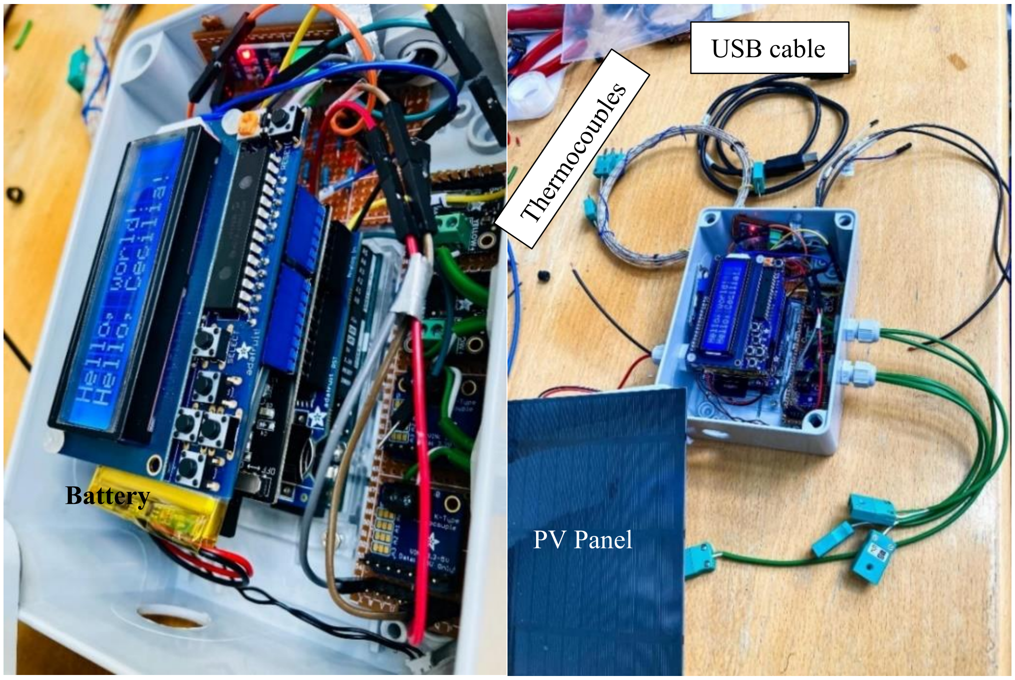


Figure 23: The complete Arduino data logger

The thermocouple sockets are wired with (green and white wires) to the 2-pin terminal blocks of the amplifiers. When connecting the sockets to the terminal block, one need to ensure that the correct poles are connected for each of the wires. The three wires: ground (brown), power (black) and data line (red) are connected from the stripboard to the data logging shield.

3.2.3 Arduino IDE Program

The data was collected with Type-K thermocouple temperature sensors using an Arduino data logger. The collected data were stored in an SD-Card.

When starting an Arduino for the first time, it needs to be connected to the laptop via a USB Type A to B 2.0 cable and the Arduino IDE program is run on the laptop. The codes which are uploaded to the Arduino, from the IDE program, is called a “sketch”. These codes remain in memory until overwritten by fresh codes, even in the absence of power. Therefore, one may create and upload code while the Arduino board is connected to a computer, and subsequently execute that code using an alternative power source (like a power bank or battery) while disconnected from the computer. This is a crucial aspect for outdoor systems [36]. The Arduino in this study was programmed to perform the following functions: To read the thermocouple signals; show the temperature readings on the LCD screen and record and save the readings on the SD Card. **Figure 24** shows a simplified flow chart of the steps from when one starts the Arduino to saving and displaying the data.

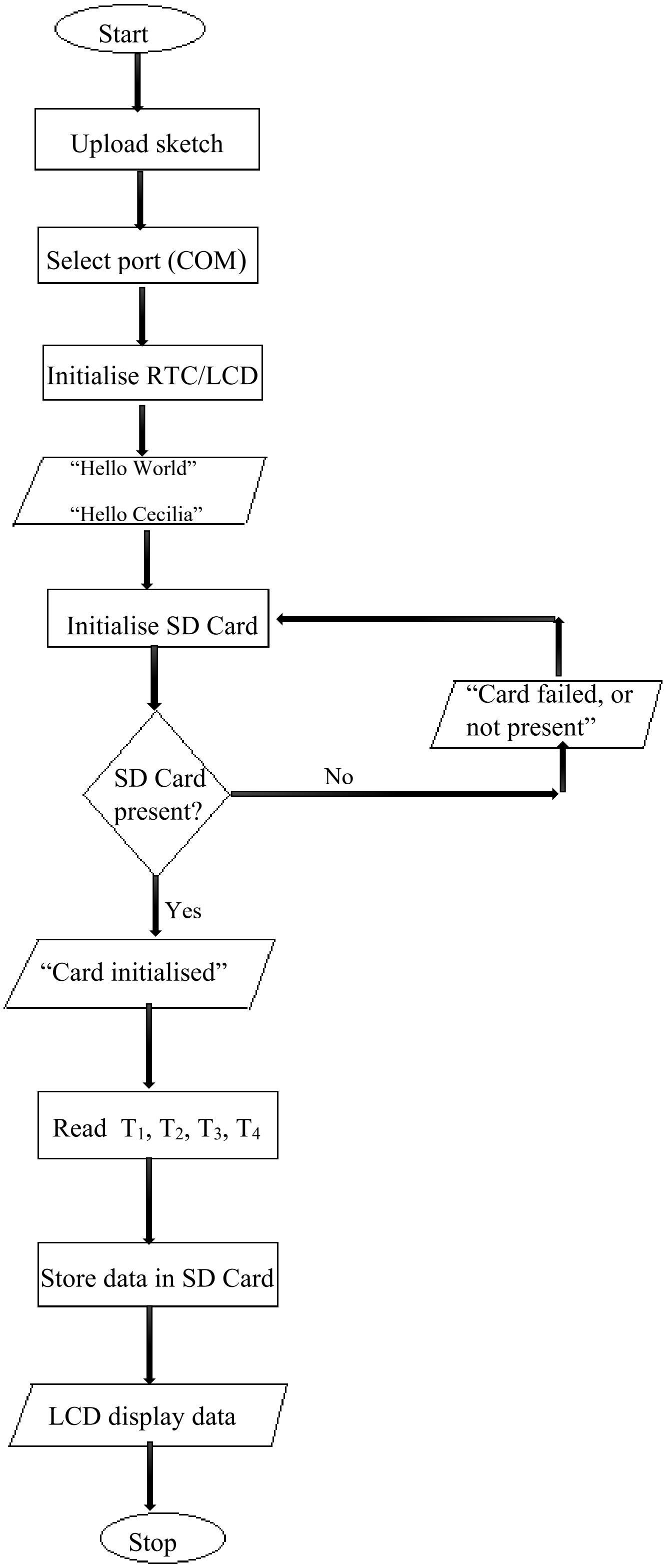


Figure 24: *Flowchart of steps taken by the Arduino IDE to acquire and store data*

3.3 Data analysis

The collected data (Temperature, time and date) was analyzed using Python programming to draw time-temperature graphs from which the efficiency and heat storage capability of the system was derived.

3.3.1 Thermal performance evaluation of the developed TES system

The effectiveness of a sensible heat storage system is assessed according to the following parameters [28,68]:

i. **Storage capacity [kWh or kJ]:** The overall energy contained inside the system is contingent upon the storage method, the materials utilized, and the dimensions of the system. The energy stored is given by the following formula [87]:

$$Q_{stored} = \sum_i m_i c_i \Delta T_s \tag{12}$$

Where m_i represents the mass of (oil + pebbles [kg]), c_i denotes the specific heat capacity of (oil + pebbles [kJ/kg.K]) and ΔT_s signifies the temperature difference between the highest and minimum storage temperatures [°C].

ii. **Power [kW]**: This refers to the energy stored per unit time that indicates the rate at which the system can be charged or discharged. This can be expressed by the following formula [87]:

$$P = \frac{Q_{stored}}{t} \tag{13}$$

Here, Q_{stored} denote the energy stored (kJ) while, t is the time (s/hrs) taken for the system to cool down to about 60°C - minimum temperature at which one may cook.

iii. **Efficiency [%]:** This signifies the ratio of energy output during discharge to the energy required for charging the storage system. It considers the energy loss during the storage duration and the charging/discharging cycle. This is calculated by boiling water for instance.

$$\eta = \frac{Q_{discharge}}{Q_{stored}} \times 100\% \tag{14}$$

$Q_{discharge}$ is the heat used to boil a quantity of water (kJ) and is denoted by the following equation [87]:

$$Q_{discharge} = m_w c_w \Delta T_w \tag{15}$$

Here, m_w denotes the mass of water being boiled (kg), c_w signifies the specific heat capacity of water and ΔT_w indicates the temperature change (°C).

iv. **Charge and discharge time [h]:** This specifies the duration required to charge or discharge the system. This can be obtained directly from the time-temperature graphs.

v. **Storage period:** This indicates the duration of energy storage, ranging from hours to months (i.e., hours, days, weeks, or months).

vi. **Cost [N$/kW or N$/kWh]:** This pertains to either the capacity (N$/kWh) or the power (N$/kW) of the storage system. The storage medium, the heat exchanger for system charging and discharging, and the expenses associated with the space and/or enclosure for thermal energy storage are incorporated. It is given by the following formulas:

$$Cost\ per\ unit\ capacity = \frac{total\ cost\ of\ the\ storage\ system\ (N\$)}{Q_{stored}} \tag{16}$$

$$Cost\ per\ unit\ power = \frac{total\ cost\ of\ the\ storage\ system\ (N\$)}{P} \tag{17}$$

3.4. Research ethic

Ethical clearance for this study was obtained from the Decentralized Ethics Committee (DEC) and research permission from the Centre for Research Services of the University of Namibia.

Chapter 4: Results

4.1 Introduction

This section presents the findings of this study as well as the key parameters that determined the viability of the developed system for domestic cooking. The data was collected with thermocouples and recorded with a data logger, logging data after every 5 seconds. This section includes the charge and discharge time graphs, the calculations of stored energy and power outputs, cooking efficiency as well as an estimation of the economic feasibility of the system for possible implementation. All of these metrics give an overall picture of the strength and weakness of the developed system. **Table 4** present the different parameter values used for performance calculations.

Table 4: *Quantities used for performance evaluations*

	Values used	
m_{oil}	$7\ Kg$	
c_{oil}	$2\,115\ J/Kg.℃$	[13]
m_{rocks}	$10\ Kg$	
c_{rocks}	$820\ J/Kg.℃$	[66]
m_w	$1\ Kg$	
c_w	$4200\ J/Kg.℃$	[13]
ρ_w	1000 kg/m^{-3}	[13]
ρ_{rocks}	2640 kg/m^{-3}	[23]
k_{ins}	$0.04\ \mathrm{W/m.K}$	[88]

4.2 Thermal performance analysis of the TES

4.2.1 Charge and discharge time

The heat storing capability of the oil/rock bed energy storing system was tested by heating/charging the system with a 12V heating elements in the laboratory. The system was heated until a temperature of about 200 ℃ (approx. The boiling temperature of sunflower oil – This was chosen as this is a temperature used for cooking majority of meals [13] and for safety considerations) after which the system was disconnected from the power source and let cool down to a temperature of about 60 ºC (the minimum temperature at which one may cook). These baseline tests were conducted to establish initial performance metrics.

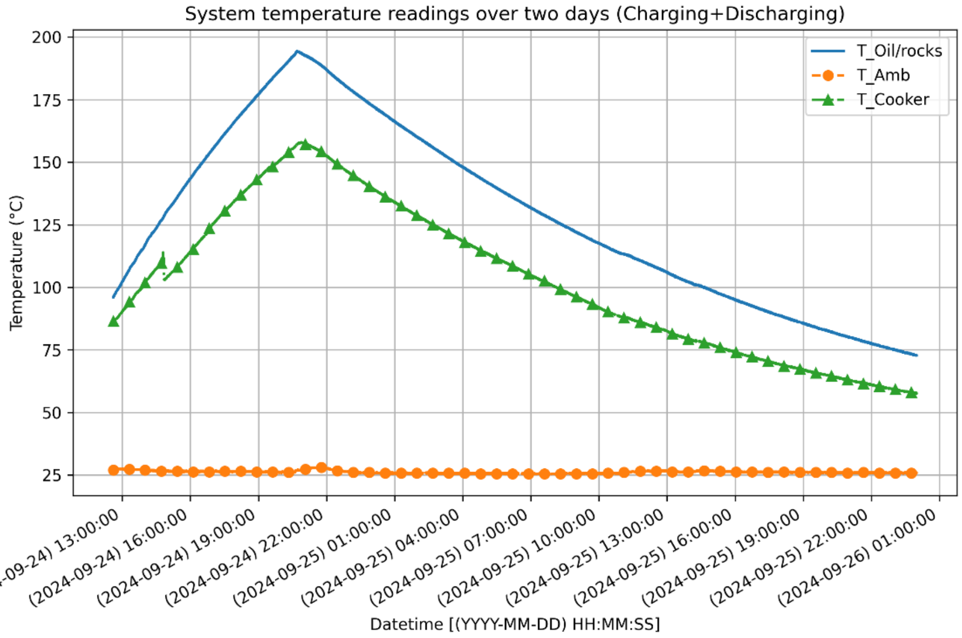


Figure 25: *System charge-discharge time*

4.2.2 Total energy stored

The total thermal energy stored in the TES system was calculated below:

$$Q_{stored} = (m_{oil}c_{oil} + m_{rocks}c_{rocks})\Delta T$$

$$Q_{stored} = (7Kg.2\,115\ J/Kg.℃ + 10Kg.820\ J/Kg.℃)\ (194℃ - 60.75℃)$$

$$Q_{stored} = 3\,065.42\ kJ\ \approx 0.85\ kWh$$

4.2.3 Power

It took the system ($t = 30\text{ hours}, 29\text{ minutes and }35\text{ seconds} = 109\ 740\text{ s}$) to cool down from $194°\text{C}\ to\ 60.75°\text{C}$. Therefore,

$$P = \frac{3\ 065.42\ kJ}{109\ 740\ s} \approx 28\ W\ = 28 \times 10^{-3}\ kW$$

4.2.4 Efficiency of the TES

The load test was conducted by boiling a liter of water, this was repeated 5 times while the system was disconnected. The first 4 liters were fully boiled while the 5th liter was boiled to about 80 °C and it remained at almost the same temperature for 4 hours until the pot was removed from the cooker as clearly shown in **Figure 26**. The temperature of the oil/rock TES at the beginning of the boiling was 200.25°C, the end of the fourth set it was at 132.25°C and after the 3 hours of the last set, it was at 103 °C.

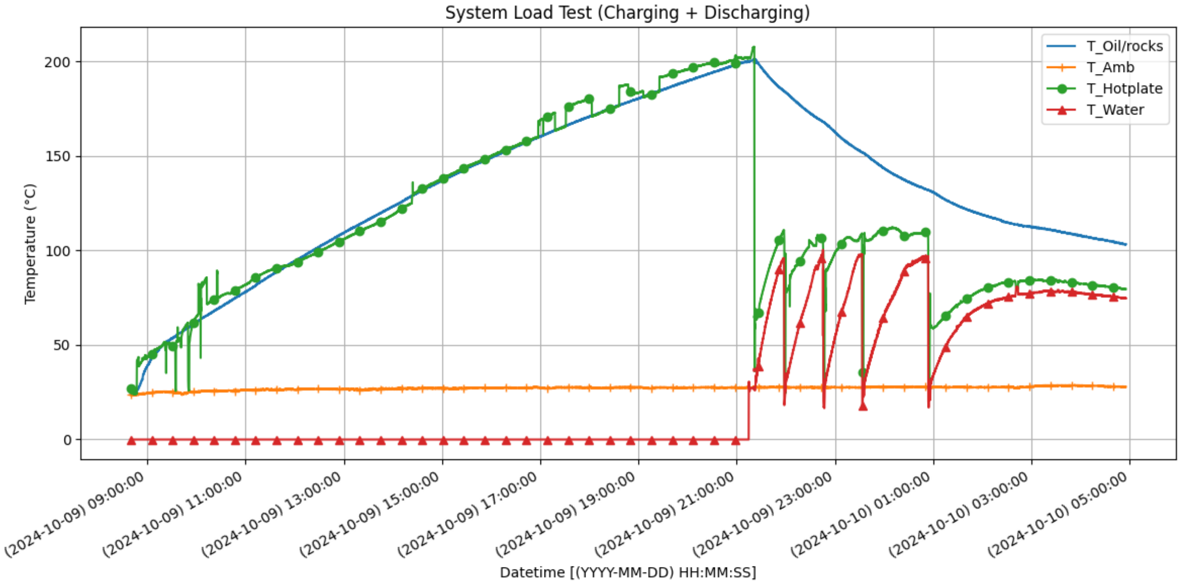


Figure 26: *Load test (Charging + Discharging)*

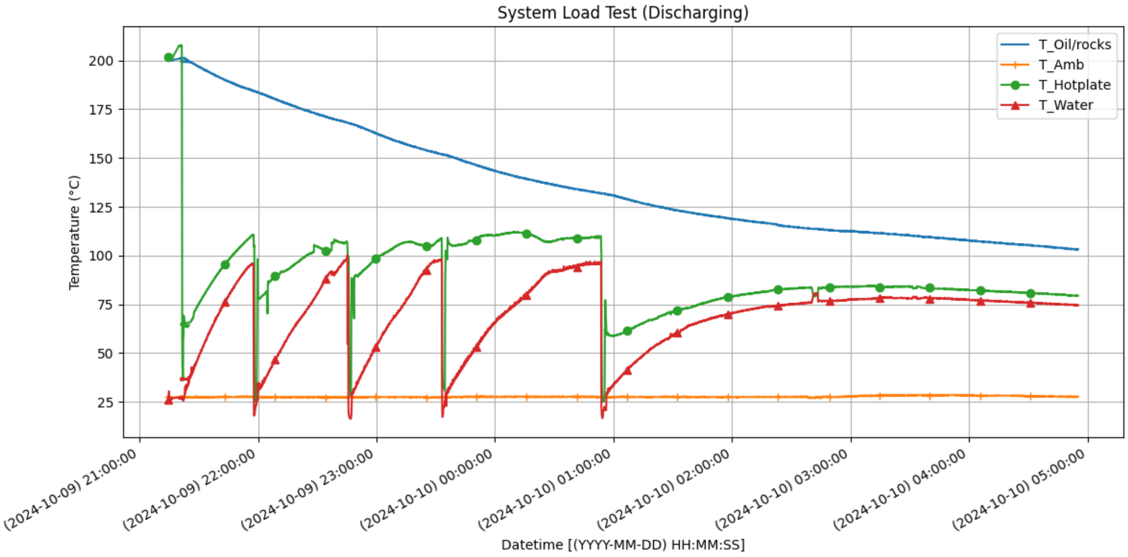


Figure 27: *Load test (boiling water)*

The cooking efficiencies for the first four water boiling sets are shown below, this compares the energy drop in storage to the energy increase in water.

$$Q_{discharge} = m_w c_w \Delta T_w \qquad ; \qquad \eta = \frac{Q_{discharge}}{Q_{stored}} \times 100\%$$

Table 5: *The efficiency of the TES system*

No.	**Initial T_w [°C]**	**Final T_w [°C]**	**ΔT_w [°C]**	**$Q_{discharge}$ [kJ]**	**Initial T_s [°C]**	**Final T_s [°C]**	**Q_{stored} [kJ]**	**η [%]**
1.	25.50	95.75	70.25	295.05	200.25	184.50	362.33	81.43
2.	25.25	98.25	73.0	306.60	183.50	168.0	356.58	86.0
3.	28.0	98.0	70	294.0	167.50	151.75	362.33	81.14
4.	25.75	96.75	71	298.20	151.50	132.25	442.85	67.33
$\eta_{average}$ = 78.98%								

In the first boiling circle, it took about 42 minutes for the temperature of water to increase from 25.5°C to 95.75 °C. The temperature of the oil-rock TES decreased from 200.25°C to 184.50°C, indicating a decrease in temperature of about 16 °C. This temperature difference was almost constant for all the four circles. The average efficiency for the four cycles was obtained as 78.98%.

4.2.5 Estimated cost of the TES

The cost of the developed TES was determined using the prices of the various components, as given in **Table 6**.

***Table 6**: The costs of different components used for the TES*

Item	**Price [N$]**
Old geyser	800
Set 4 of pots	400
DC kettle 'heating element'	400
Sunflower oil (7*l*)	330
Insulation	430
Labor	1500
TOTAL	**3 860**

$$Cost\ per\ unit\ capacity = \frac{total\ cost\ of\ the\ storage\ system\ (N\$)}{Q_{stored}}$$

$$= \frac{N\$\ 3860}{3\ 065.42\ kJ} = N\$\ 1.26/kJ$$

$$Cost\ per\ unit\ power = \frac{total\ cost\ of\ the\ storage\ system\ (N\$)}{P}$$

$$= \frac{N\$\ 3860}{28\ W} = N\$\ 137.86/W$$

4.2.6 Cooking performance evaluation

The cooking performance of the system was tested by cooking 300g of rice and 300g of dry beans, simultaneously using the stored heat, without recharging the TES system. The system was charged to 200 °C and then got disconnected for cooking on the stored heat. It took rice about 43 minutes (23:01-23:43) to get fully cooked after which rice was removed from the pot and replaced with dry beans. The beans took about 4h and 20 mins (23:51-04:30) to get fully cooked. The pot was then left on the cooker until the morning.

The spikes in the graphs were a result of frequent opening of the pot during the cooking to see if the food was ready.

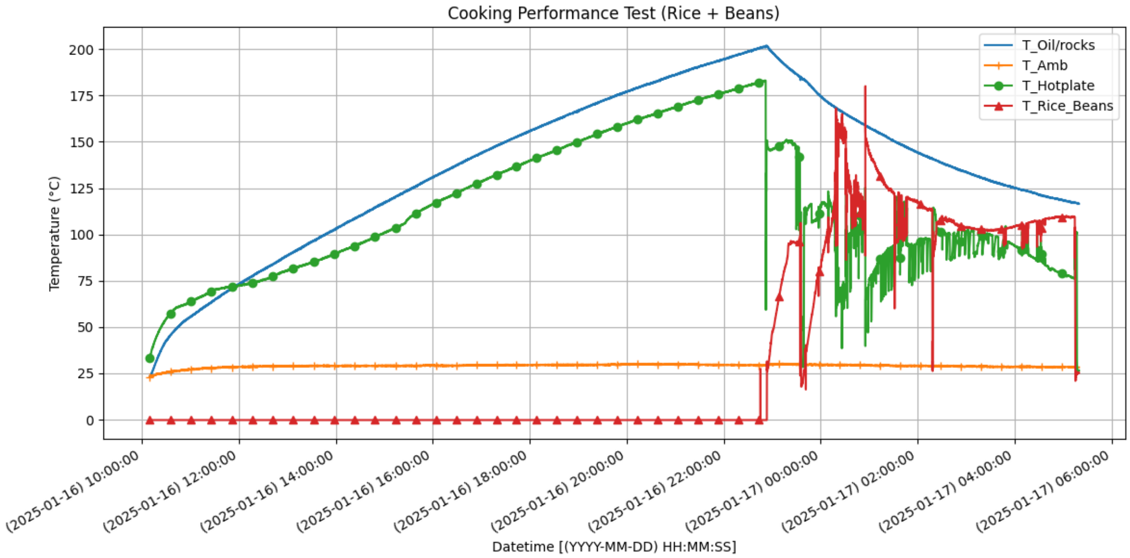


Figure 28: *Cooking test temperature profiles*

Figure 29: *Cooked rice and dry beans*

Chapter 5: Discussions

The purpose of this study was to design and construct an oil/rock bed TES system using locally available materials so as to provide an inexpensive and effective TES system for domestic cooking. Prior studies guided the conceptualization and development of the system, prioritizing affordability and accessibility. All experiments were done in the laboratory, and charging was done using a 12V (120W) heating element. The system used sunflower cooking oil and rock pebbles, which are moderately thermally stable and have high heat capacities [65,87]. These choices are consistent with research that has proposed the use of both liquid and solid mediums in TES systems for the improvement of heat transfer rates [56].

The incorporation of Aerolite insulation reduced heat losses, a parameter that affects the system's performance [13,23]. The reuse of an old geyser as the main body of the system demonstrated innovation in repurposing materials, reflecting sustainability principles often advocated in TES designs [27]. In addition, the decision to rely on natural convection as a heat transfer mechanism aligned with the simplicity and accessibility needed for off-grid applications.

The Arduino data logger played a pivotal role in this study, enabling precise monitoring of the system's temperature over time. The integration of microcontroller-based monitoring systems is well supported in the literature where the collection of real-time data is considered useful for performance measurement in energy systems [37,42,73]. The successful development of this low-cost logger further supports the feasibility of integrating this type of cheap technology into energy systems. It also shows how this method can be used in future research or practice where constant monitoring of performance is desirable.

The system highlighted its great heat retention capacity by showing a prolonged discharge time, which maintained useful temperatures for more than thirty hours. In contrast, the system created by Okello, et al. [23], had an excellent general performance but its heat retention time was just 14 hours. This might be explained by the low grade of the utilized insulation. Lugolole et al. [56] who noted that oil-based TES devices show notable thermal inertia and enable slow heat release complement the results of this study. This view is also supported by Mawire's [65] discovery of remarkable thermal stability and heat retention characteristics of sunflower oil as a reasonable heat storage media.

The use of sunflower oil and rock pebbles as storage medium, together with the insulation utilized in this study, helped the system to retain a high temperature for a longer period, thereby allowing cooking even in non-sunshine hours. This result presents a workable solution to the limitations of solar cookers during non-sunshine hours, thereby addressing the problem statement [13,23]. However, the relatively long discharge time suggests that while the system excels at retaining heat, its heat transfer rate could benefit from optimization [89], as quicker discharge might be preferable for certain cooking needs. Optimizing the design to balance discharge time with thermal energy availability is still an area for development.

Overall, the energy storage of the system was 0.85 kWh, and the power was 0.028 kW. Although these numbers are relatively small, they demonstrate the TES system's capacity to store and discharge energy at a level adequate for residential cooking [23], thereby achieving the research goals outlined in this study. Although these values show that the system is quite feasible, the fact that the power output is lower than in other systems [13,23], is a drawback.

The constructed system reached notable thermal performance levels when tested under load conditions. During water boiling tests, the system showed an average efficiency rate of 78.98%, which demonstrated its capability to convert stored thermal energy into usable heat for cooking needs. This system’s performance is comparable to other thermal energy storage systems documented in the literature [13,23], found using the same storage materials. For example, Kajumba et al. recorded a maximum efficiency of 52%, on the other hand, Okello et al. claimed an efficiency of about 65%. The efficiencies of TES systems are based on material selection and design and it is often challenging to balance the two as it has been observed in previous research, where balancing cost, simplicity, and performance are typical challenges [90].

The system demonstrated consistent efficiency results when boiling four liters of water, which confirms that the selected materials and design choices were appropriate for practical cooking operations. The obtained high efficiency proves that oil/rock bed TES systems demonstrate utility in solar cooking applications since reliable energy output remains essential. The system's practical reliability was further emphasized by the sequential boiling test, which successfully accomplished the objective of boiling water multiple times without active heating, a feature that is essential for domestic cooking applications.

The system's estimated cost of N$ 3,860 is relatively low and significant for adoption, particularly in rural areas. The calculated cost per unit capacity of N$ 1.26/kJ and per unit power of N$ 137.86/W favorably compares to other small-scale TES systems documented in literature [91]. This cost-effectiveness is in line with this study's objective of proposing a system that fits Namibian cooking practices and is affordable.

However, cost does not have to come at the expense of performance. Thus, the system realizes the goal of providing affordability, but more optimization is required to increase the power and efficiency without a proportional rise in cost. The work of Özbuldu and Karaca [92] on basalt stones as heat storage materials suggested that there could be a better cost-performance balance by integrating the use of the material or through economies of scale in manufacturing.

Moreover, the cooking performance of the oil/rock bed TES system gives useful information on the feasibility of the TES technology for domestic cooking. During testing the TES system was heated to 200 °C and disconnected from power. The stored heat was then used to cook 300 g of rice and 300 g of dry beans in a single cycle without recharging the TES system. The rice only took approximately 43 minutes to cook thoroughly; the time was consistent with typical cooking durations for rice.

After the rice, the beans were cooked, where it took approximately 4 hours and 20 minutes before they were well cooked. This extended cooking time for beans, which are typically known to take long to cook because of their hardness and density, was an excellent way of establishing that the system can maintain heat release for long periods. After the beans were cooked, the pot was kept on the cooker for the next two hours, which again proved the continuous working of the TES system on residual heat.

These results reaffirm the usefulness of the developed TES in accomplishing various cooking tasks with a single cycle and demonstrate its potential for realistic household application in off-grid settings. The findings are consistent with the earlier studies [13,23]. Furthermore, the ability of the system to cook energy-intensive foods such as dry beans is an added advantage, which makes the system suitable for areas where long cooking times are needed due to the type of diet or staple foods. The system demonstrated by Kajumba [13], cooked 250g of rice in 30 minutes and unlike the TES in this study which was tested solely on stored heat, the oil-rock pebble system developed by Okello et al. [23], was tested to cook 500g of beans and rice while it was charging and it took 2 hours to cook the beans.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

The aim of this research was to develop and assess the performance of an oil/rock bed sensible TES system for solar cooking. The study was able to achieve the main objectives and prove the viability of the TES system in storing and releasing thermal energy for domestic cooking. With the utilization of sunflower oil and rocks as the storage mediums, the system realized great accomplishments with long discharging duration and constant and desired energy output at desirable cooking temperatures. Furthermore, the incorporation of a data logger enhanced the monitoring and evaluation process, constituting a strength in the research methodology.

The research proved that the oil/rock bed TES system could store large amounts of thermal energy and was capable of maintaining practical cooking temperatures for more than 30 hours with the overall thermal energy storage capacity of $0.85\ kWh$. The system's capacity to sustain temperatures ideal for cooking for a long duration addresses a major concern in solar cooking technologies. Furthermore, the boiling tests revealed an average efficiency of 78.98%, indicating the system's suitability for off-grid and rural households. The cost-benefit analysis showed that the system is fairly cheap, costing N$ 1.26/kJ and N$ 137.86/W, which makes the system a viable solution to conventional cooking methods.

The cooking performance tests showed that the system can maintain adequate heat for long cooking processes, like cooking rice in 43 minutes and dry beans in 4 hours and 20 minutes using stored thermal energy without recharging. These results demonstrate how the system can address a wide range of cooking requirements in rural settings, especially for foods that take longer to cook.

Nonetheless, the study encountered several obstacles that constrained its potential results. The absence of financing limited the assessment of the system's capabilities, especially in testing direct solar charging via a photovoltaic (PV) panel. Lack of such assessments restrained comprehensive performance evaluations of the system under solar energy conditions.

Overall, the results of this research offer insights into the feasibility and viability of employing oil/rock bed as TES for domestic cooking. It therefore emphasizes the right choice of materials for energy storage and shows how such systems could provide sustainable and cheap solutions to energy problems faced by rural and off-grid communities. Altogether, it can be stated that the research has met its primary goals, although further efforts shall be made to overcome the revealed limitations. Future research should also focus on optimizing the TES system through design. This study has provided a solid foundation for improving TES technologies and it presents a framework for scaling up such solutions for the improvement of energy access in rural areas.

6.2 Recommendations

Drawing on the results and conclusions of this study, the following suggestions are made:

- There exists a need for comprehensive testing of direct solar charging methods, which would provide a more complete understanding of the system’s performance in practical solar cooking applications.
- The TES system was tested inside a laboratory by heating it with a single 12V (120 W) element, this resulted in the system taking too long to reach the desired temperatures. Future studies may avoid this by using either two elements or replacing the single element with a much higher rated element.

- Future work should be conducted to test and compare the viability of using other locally available edible oils as well as other non-edible oils such as synthetic heat transfer oils.
- Additional studies should be done to determine the potential of oil/rock TES system to be scaled up to cater for larger commercial cooking needs such as those in schools, hospitals and community kitchens.

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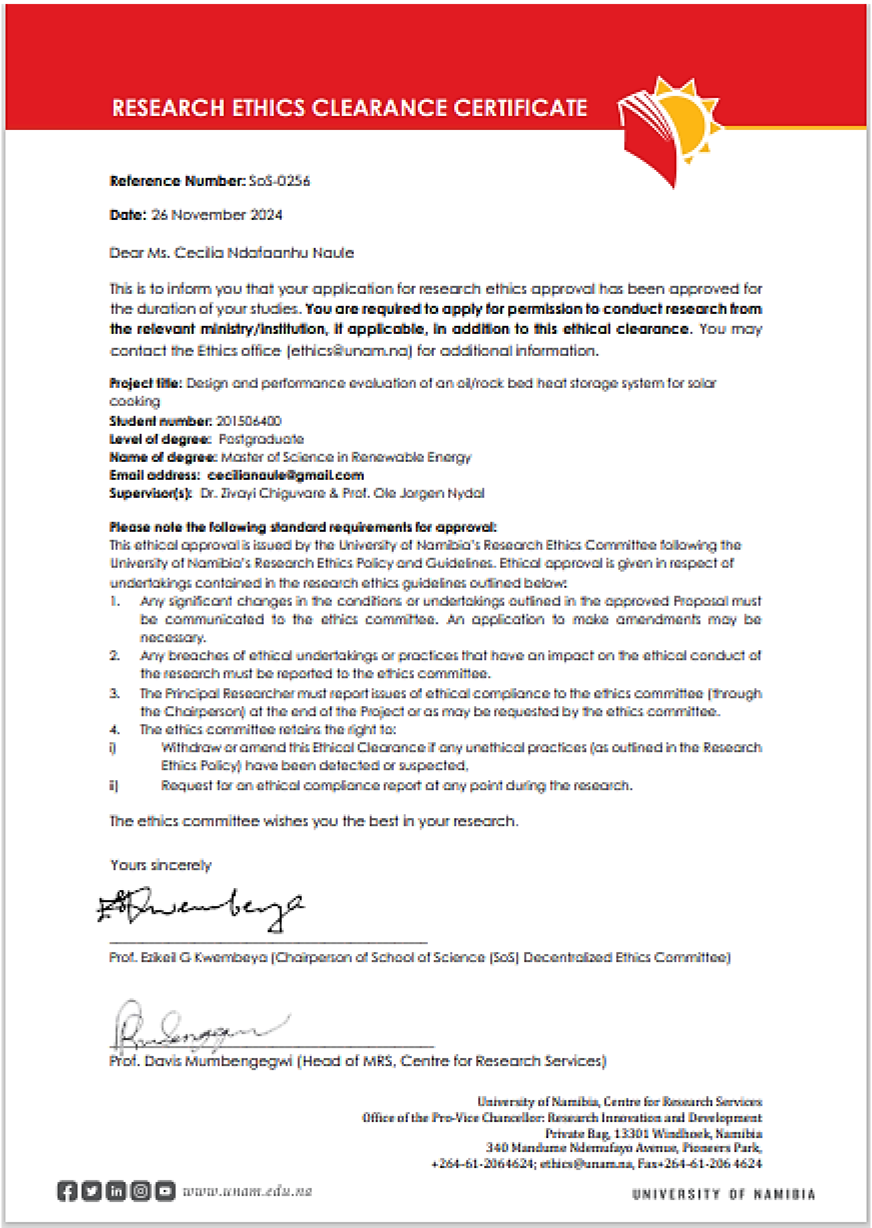
Appendices

Appendix A: Ethical Clearance Certificate



RESEARCH ETHICS CLEARANCE CERTIFICATE

Reference Number: SoS-0256

Date: 26 November 2024

Dear Ms. Cecilia Ndafaanhu Naule

This is to inform you that your application for research ethics approval has been approved for the duration of your studies. **You are required to apply for permission to conduct research from the relevant ministry/institution, if applicable, in addition to this ethical clearance.** You may contact the Ethics office (ethics@unam.na) for additional information.

Project title: Design and performance evaluation of an oil/rock bed heat storage system for solar cooking
Student number: 201506400
Level of degree: Postgraduate
Name of degree: Master of Science in Renewable Energy
Email address: **cecilianaule@gmail.com**
Supervisor(s): Dr. Zivayi Chiguvare & Prof. Ole Jorgen Nydal

Please note the following standard requirements for approval:
This ethical approval is issued by the University of Namibia's Research Ethics Committee following the University of Namibia's Research Ethics Policy and Guidelines. Ethical approval is given in respect of undertakings contained in the research ethics guidelines outlined below:

1. Any significant changes in the conditions or undertakings outlined in the approved Proposal must be communicated to the ethics committee. An application to make amendments may be necessary.
2. Any breaches of ethical undertakings or practices that have an impact on the ethical conduct of the research must be reported to the ethics committee.
3. The Principal Researcher must report issues of ethical compliance to the ethics committee (through the Chairperson) at the end of the Project or as may be requested by the ethics committee.
4. The ethics committee retains the right to:

i) Withdraw or amend this Ethical Clearance if any unethical practices (as outlined in the Research Ethics Policy) have been detected or suspected.
ii) Request for an ethical compliance report at any point during the research.

The ethics committee wishes you the best in your research.

Yours sincerely

Prof. Ezkeil G Kwembeya (Chairperson of School of Science (SoS) Decentralized Ethics Committee)

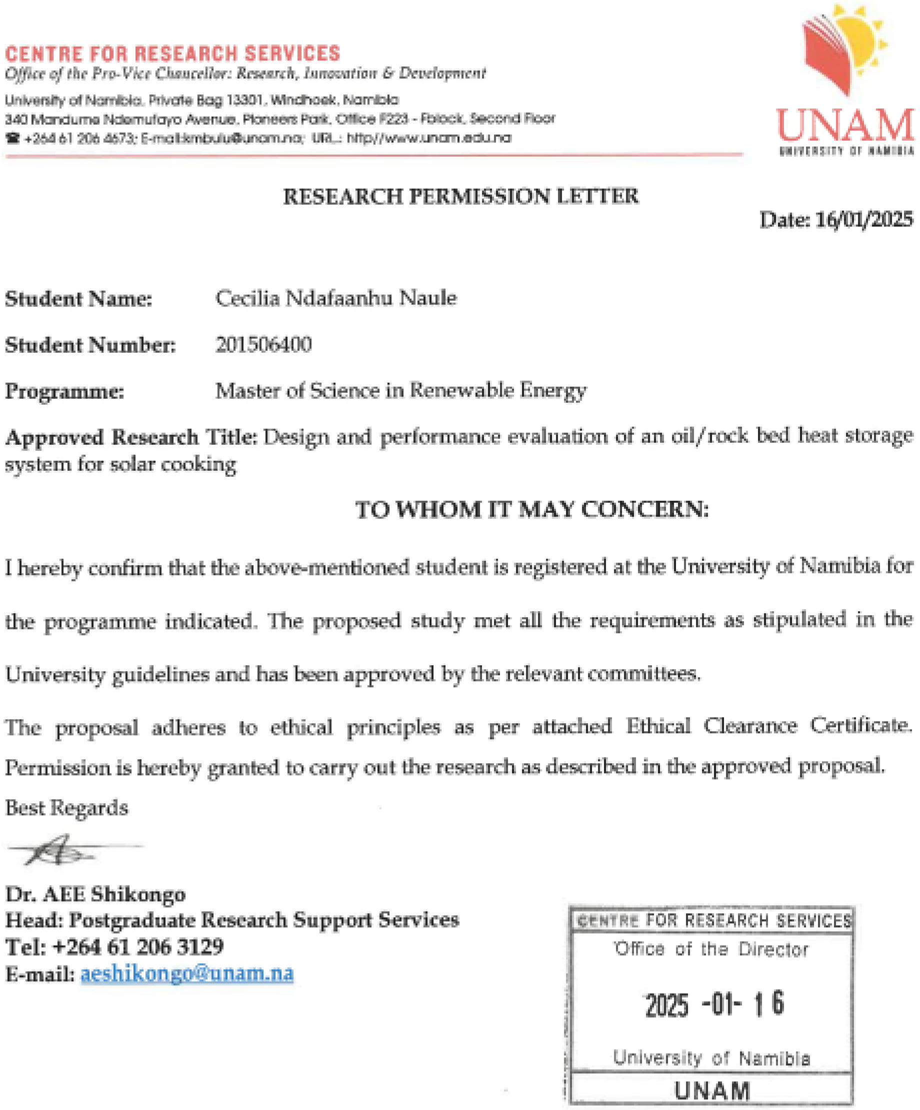
Prof. Davis Mumbengegwi (Head of MRS, Centre for Research Services)

University of Namibia, Centre for Research Services
Office of the Pro-Vice Chancellor: Research Innovation and Development
Private Bag, 13301 Windhoek, Namibia
340 Mandume Ndemufayo Avenue, Pioneers Park,
+264-61-2064624; ethics@unam.na, Fax+264-61-206 4624

www.unam.edu.na

UNIVERSITY OF NAMIBIA

Appendix B: Research Permission Letter



CENTRE FOR RESEARCH SERVICES
Office of the Pro-Vice Chancellor: Research, Innovation & Development
University of Namibia, Private Bag 13301, Windhoek, Namibia
340 Mandume Ndemufayo Avenue, Pioneers Park, Office F223 - Fblock, Second Floor
☎ +264 61 206 4673; E-mail:kmbulu@unam.na; URL: http//www.unam.edu.na
UNAM
UNIVERSITY OF NAMIBIA

RESEARCH PERMISSION LETTER

Date: 16/01/2025

Student Name:	Cecilia Ndafaanhu Naule
Student Number:	201506400
Programme:	Master of Science in Renewable Energy

Approved Research Title: Design and performance evaluation of an oil/rock bed heat storage system for solar cooking

TO WHOM IT MAY CONCERN:

I hereby confirm that the above-mentioned student is registered at the University of Namibia for the programme indicated. The proposed study met all the requirements as stipulated in the University guidelines and has been approved by the relevant committees.

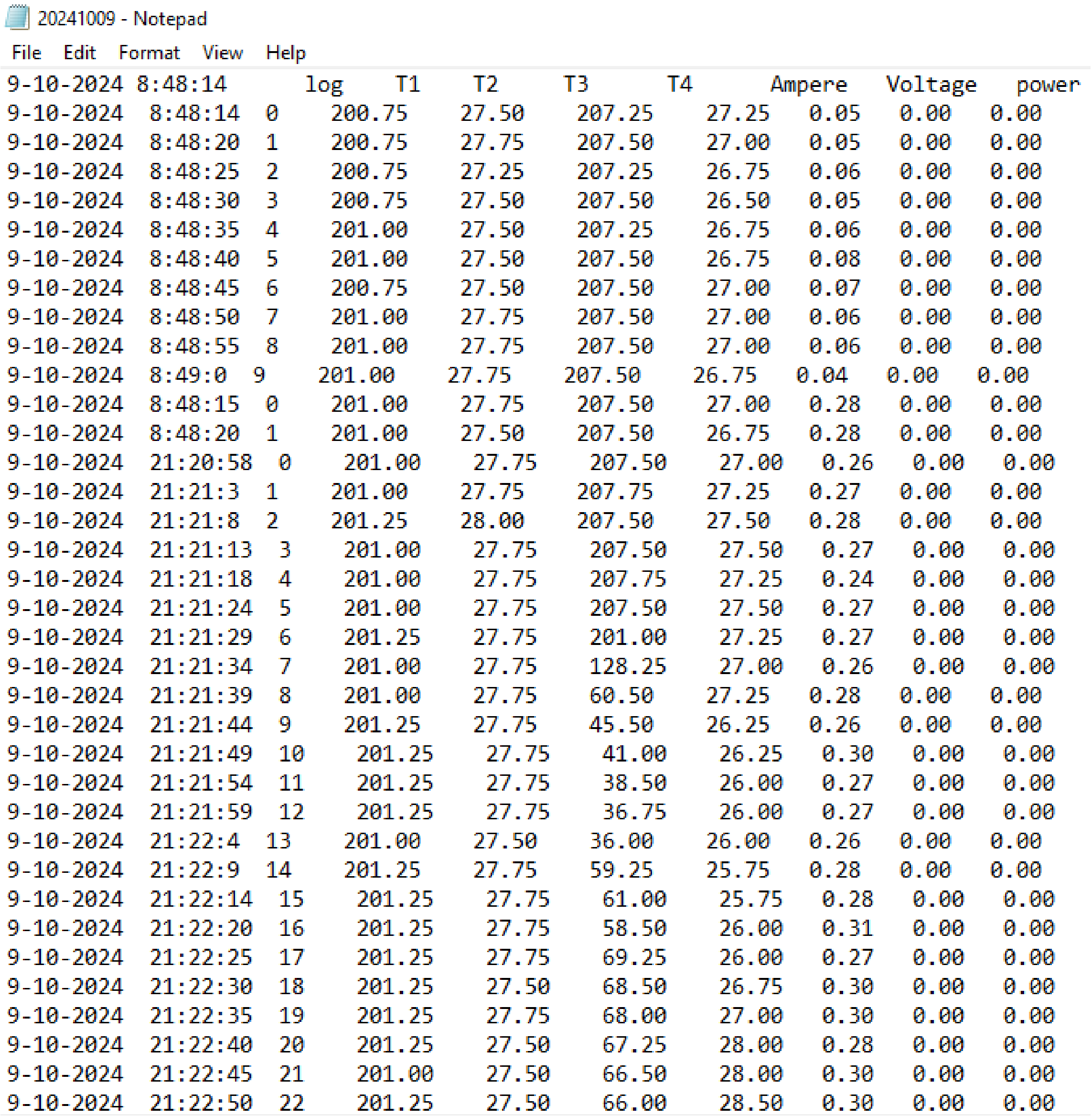
The proposal adheres to ethical principles as per attached Ethical Clearance Certificate. Permission is hereby granted to carry out the research as described in the approved proposal.

Best Regards

Dr. AEE Shikongo
Head: Postgraduate Research Support Services
Tel: +264 61 206 3129
E-mail: aeshikongo@unam.na

CENTRE FOR RESEARCH SERVICES
Office of the Director
2025 -01- 16
University of Namibia
UNAM

Appendix C: Sample raw data



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9-10-2024  21:21:59  12    201.25    27.75    36.75    26.00   0.27   0.00   0.00
9-10-2024  21:22:4  13    201.00    27.50    36.00    26.00   0.26   0.00   0.00
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