A Holistic Approach to Affordable Housing

A Major Qualifying Project Report
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Abstract

Lack of affordable housing is a major global issue in the 21st century. This is especially prevalent in developing countries, where millions are earning less than U.S. $1-2 per day. We used our understanding of engineering and finance to provide a holistic solution for affordable and self-sufficient housing that can be applied anywhere in the world. Our building design integrates active and passive solar power, wind power, and water filtration and collection in order to generate its own electrical power and maintain its own drinking water, respectively. The mechanical and thermal properties of the building materials were tested to meet structural standards. A multi-tier financial model was then developed for our self-sufficient low-cost housing for families of different income levels.

Acknowledgements

This project was conceived and headed by WPI's Provost, Winston Soboyejo. Associate Professor, Aaron Sakulich aided in the building materials portion of this project. Ali Salifu aided the water filtration portion of this project. Deborah Oyewole, Tofunmi Ogunfunmi and Jaya Cromwell all greatly contributed to the success of this project. Associate Professor, Leonard Albano aided with the structural analysis for this project. And finally, Oluwaseun "Kenny" Oyewole deserves special recognition as his mentorship and guidance throughout the entirety of this project were instrumental in our success. He also played a pivotal role in aiding the energy portion of this project.

Executive Summary

This project was focused on designing an affordable and fully sustainable house, as well as outlining a sophisticated plan to realistically implement the house in Nigeria. For our purposes, “affordable” will be defined as a home that can be financed at a rate equal to or less than 35% of the income of the family, whether the family is making $1-2 or $20-50 a day. In context, “sustainable” will be defined as a home that is built from inexpensive and abundant natural resources, producing all of its energy autonomously, and collects and filters all of its water autonomously.

To achieve this, we took a holistic approach to the global issue. This involved analyzing the viability of sustainable technologies, as well as creating a detailed financial plan and community model to ensure the homes were affordable. This approach allowed us to properly validate our technologies, as well as their full integration into a financial model and cost analysis.

For energy production, our team focused on evaluating the capabilities of two technologies: wind turbines and solar panels. Thermoelectric technology was also considered as a source of energy production, but our initial research showed that the current technology available is not suitable within the context of our designs. For energy provided through solar panels, we tested battery charging capabilities under various real and simulated weather conditions. These tests allowed us to learn how robust solar panels are as a means of reliable energy production for our home. Our next source of sustainable energy involved a bamboo wind turbine. We tested its capabilities under various wind speeds in relation to average wind speeds in Nigeria. This gave us a sense of the wind turbine’s energy generating capabilities on its own. We then combined the solar and wind turbine into a singular integrated charging system, with the idea that the wind turbine could backfill the energy requirements during the night, when the solar panel is inactive. Additionally, charge and discharge rates were determined for the batteries we used in our designs. The data from all of these tests were analyzed graphically in order to give us an understanding of how we could realistically implement a reliable energy system into the house.

With promising results for our different technologies, we were able to determine what appliances we would be able to power from the electricity generated. To get a better understanding of stakeholder needs and to ensure that our designs were solving the correct problems, one team member conducted conversations in person with people in Nigeria. The goal was to determine what the people would truly want and need in their homes. These preferences were taken into consideration in the final design of the house. From this we moved on to the affordable and sustainable building design.

Building materials are typically about 70% of construction costs in a housing design. Realizing this, our team utilized affordable and readily available materials in our designs. Clay and cement mixtures of 70/30 and 80/20 % volume ratios were tested. In addition, the usability of sandwich panels was determined. To ensure that the building materials were structurally sound, mechanical properties of these materials were studied. To incorporate passive solar technology into the sustainable building design, the thermal properties of these materials were also tested. Test methods used include: guarded longitudinal comparative calorimetry, differential scanning calorimetry, 3-point flexural tests, and compression tests. Through these methods, we were able to understand the materials' behaviour in structural applications and compare it to the behavior of traditional materials. By understanding the thermal properties of these materials, thermal diffusivity rates could be used in determining passive solar opportunities. More specifically, the thickness of the building's outer walls were determined to take the best advantage of the sun's thermal energy and maintain comfortable temperature levels throughout the building.

The last technology that was validated and incorporated into our holistic approach involved providing clean water. To tackle this global issue, our design integrated both rainwater harvesting and filtration through ceramic water filters. The effectiveness of rainwater harvesting in Nigeria was validated through research and calculations, while the scalability of ceramic water filters was studied. In order to familiarize ourselves with the science behind how ceramic water filters work, our team was able to take part the filter manufacturing process. Several filters made of specific proportions of clay, sawdust, and water were created by properly mixing, pressing, and firing the filters. In addition, flow rate analysis was conducted on varying volumetric proportions of clay and sawdust. Using this data, a multiple filter system was designed and created in order to maximize the volume of water available from a system of five ceramic filters. The autonomous water filtration system was successful in improving potable water availability as well as providing insight into the scalability of the technology.

Finally, after testing and proving these sustainable technologies individually, a fully integrated home was carefully designed. The total cost of the home was taken into consideration in every detail of the design so that the final model was affordable to even the lowest of incomes. Based on the single home design, a 200 home community model was also created and an in depth financial was created. In total, each home would cost approximately $25,000, which includes the home with all appliances, community infrastructure (roads and recreational areas), and clean drinkable water. By providing housing that is affordable and sustainable to even the lowest incomes in developing nations, our holistic approach has the potential to create a lasting impact on a global scale.

ES1: Integrated Design Model

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1.0 Introduction

Millions of people around the world lack access to basic necessities such as stable housing, clean water, and electricity. Most notably, lack of affordable housing is a major global issue in the 21st century. These issues are especially prevalent in developing countries where hundreds of millions are living in unsuitable shelters and are earning less than U.S. $1-2 per day. In this project, we use our understanding of engineering and finance to design an affordable and sustainable home that is accessible to the lowest income citizens of a society and replicable in any country in need. With this in mind, there are two fundamental questions that need answering:

1. **Why do we need to design a sustainable house?**

Building a sustainable house involves sustainable water collection and filtration, energy generation and building materials. In essence, this means that the house collects and filters its water on its own, produces its own energy and is made from sustainable materials that are readily available. This creates a completely autonomous house that doesn't rely on pre-existing infrastructure for energy or water. Since our target audience is low-income families in developing countries like Nigeria, we recognize that the government may unreliable and not stable enough to provide consistent energy and water to low-income families. By creating a unique model that leverages the aforementioned technologies, we are able to detach the house from government control and sufficiently meet the needs of a typical low or middle-income Nigerian family.

2. **Why do we need to design an affordable house?**

The answer to this question may seem obvious at first; with our target market being low-income people, we must be able to design a house that is financially feasible for them to purchase. However, this question goes much deeper than simply lowering the cost of the house. We must also consider the risk factors that affect the cost of the house and how we can work to mitigate them. Namely, we must acknowledge the total cost of the land, labor, building materials, technology and the financing options that banks may present prospective home-buyers. We must account for these factors when designing an affordable home, as they can drastically affect the price of the house despite our best efforts in other areas that detach the home from government and big-bank intervention.

With these two question in mind, we focused on understanding more prerequisite information before beginning to design the house. We explored concepts such as basic housing requirements, energy needs, water needs and sustainable housing in order to gain fundamental background knowledge to achieve a more holistic solution.

2.0 Background

This chapter provides a brief overview of basic housing requirements, energy needs, clean water needs, affordable housing, sustainable housing, and current research in housing that is both sustainable and affordable.

2.1 Housing Requirements

World housing is an issue that affects hundreds of millions of people every year. McKinsey & Company's Global Institute estimates 330 million urban households around the world live in substandard housing or are so financially stretched by housing costs they forgo other basic needs like food and health care. They further discuss this issue in their "A blueprint for addressing the global affordable housing challenge," estimating that by 2025 about 440 million urban households (around 1.6 billion people) will occupy inadequate, unsafe, and crowded housing. In Nigeria specifically, where the total percentage of people below the National Poverty Line is 67% ($1.90 PPP per day) the housing situation is grim.

Everyone should have a fundamental human right to housing, and at the very minimum, adequate shelter. In order to fix this growing housing problem, it is important to first define what constitutes adequate shelter. According to the United Nations Habitat Agenda, "adequate shelter means more than a roof over one's head. It also means adequate privacy; adequate space; physical accessibility; adequate security; security of infrastructure, such as water-supply, sanitation and waste- management facilities; suitable environmental quality and health-related factors; and adequate and accessible location with regard to work and basic facilities: all of which should be available at an affordable cost." Besides a shelter from the elements, a home should provide privacy and space, basic infrastructure such as a water supply, and an accessible location to facilities. It is important to take all of these aspects into account when designing housing because missing even just one these necessities can create an undesirable home.
In developing countries, housing investments 3-10% of GDP and it is the largest item of non-food household expenditure and the most valuable asset possessed by most low-income households. Mass 'public' construction programs have proven to be ineffective at resolving the

housing crisis in developing countries. Even with plentiful of labor, there is a lack of skilled worker, operatives, and constraints to the supply of building materials. Finance has proven to be a key aspect in the success of success of sustainable housing in developing countries.

2.2 Affordable Housing

Affordable housing is generally known as housing that does not exceed 30% of a household's income. In some developing countries, as high as 70% of its population is living below the poverty line (less than $1 per day), it is difficult to provide housing that is deemed affordable but still meets provides basic requirement of adequate shelter.

In developed countries such as the United States, the government has implemented systems and subsidies that allow individuals to afford adequate houses that meet their standard of living. In developing countries, such systems are not in place which makes affordable housing in such places look like a unattainable goal. In addition to this, the cost of building material plays a big role in the inability of people to afford housing. Interestingly, building materials make up 70% of housing cost yet 80% of the world use building materials that only the richest 20% can afford.

This paper presents an approach to housing that utilizes low cost technology to homes, making them more affordable. This approach will be adaptable in that it can be scaled up or down depending on the region or individual desires.

2.3 Sustainable Housing

The concept of sustainable housing is not new. But the vast nature of its applications means that new forms of sustainability are being developed constantly. For the sake of this paper sustainability is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Kuhlman and Farrington, 2010).Therefore sustainable housing is housing that provides all it needs (energy, shelter etc.) without hindering the abilities of future generations to do so.

In third world countries were a majority of the population are barely able to feed themselves, it is almost impossible for individuals to pay for the energy needs of their household without some intervention. This is where the concept of sustainable housing in such countries becomes very beneficial. Solar and wind are one of the freest forms of energy available is developing countries like Nigeria. Implementing a system were the cost of providing these energies to individuals is greatly reduced will allow even people of low income to afford suitable housing. In addition to this, by implementing sustainability in the building materials by utilizing materials that are readily available in such regions also reduces the cost of building such houses.

In this paper we are going to explore how sustainability can be applied in housing design in order to meet the demands of people of low income in developing countries. We will also explore the scalability of this technology in order to meet the demands of middle and high income people.

For our purposes, our definition of affordable sustainable housing is as follows: Housing that is both affordable to low-income people and gets its energy, purified water on its own and is made from sustainable building materials.

2.4 Combining Affordable & Sustainable Housing

In the U.S., affordable sustainable housing is typically divided into separate categories, affordable and sustainable respectively, and are thus addressed separately. Government programs such as the Affordable Housing and Sustainable Communities (AHSC) program in California aim to first create affordable housing for low-income people. This housing is characterized by its overall low-cost to build and "assistance" based financial model for ease of payment. These types of housing endeavors are usually referred to as "projects" and are categorized by their area and size (HCD).

Sustainability in the projects appear to usually be an afterthought, and typically only consist of abiding by building codes in order to reduce greenhouse gas emissions via the Greenhouse Gas Reduction Fund (GGRF) (HCD). The current issue with implementing a sustainability model into architectural plans is the increased cost for the building. It takes a lot of careful planning and analysis to create sustainable housing, and for an architect that means hiring the correct people and obtaining the proper building materials. This costs more money than simply building based on already existing non-sustainable models available (Cohen 1).

In Nigeria, sustainable affordable housing is an extremely new and lucrative architectural endeavor because of the overwhelming need for affordable housing that can provide sustainable solutions for a family's basic necessities. The need is so great, in fact, that "80% of Nigerians live in indecent, informal housing structures with no basic amenities and in deplorable conditions." (Ohajuruka). Affordable sustainable housing aims to target this large portion of the Nigerian population and provide them with a substantial upgrade to their current housing. This upgrade includes the following:

- Free energy collected from the sun via solar panels
- Access to potable water
- Structurally sound housing made from sustainable building materials

These three essential pillars of Nigerian affordable sustainable housing provide for a major leap forward for a majority of the population. While these solutions haven't been implemented at a large scale yet, Nigerian architectural companies are looking to take advantage of this golden opportunity (Ohajuruka).

2.5 Energy Needs and Potential Approaches

Electricity can easily be taken for granted. Light switches are turned on without ever thinking of all the infrastructure that was need to make that simple task possible. To some, living without electricity is still part of their every day challenges. A lack of electricity can limit productivity for individuals, but on a larger scale, it can act as a hindrance to an entire nation's growth. In fact, "A billion people still live without electricity. Hundreds of millions more live with unreliable or expensive power, which poses a key barrier to economic development in emerging economies" (The World Bank Group 2018). Our goal is to help solve this energy problem by providing sustainable and integrated solutions. More specifically, our holistic design includes energy from multiple sustainable sources, including wind and active solar collection (solar cells).

2.5.1 Wind Energy

Wind energy has been around for centuries, and is commercially utilized in order to power cities. They are especially powerful on long flat areas and on the ocean, where they are not blocked by any building or structure. Their design allows them to catch the wind and rotate their massive turbine in order to generate electricity. It uses the pressure difference laws of physics and aerodynamics to produce a force from a pressure difference which in turn drives the turbine in rotation, spinning the connected electric motor producing electricity. Wind turbine can range from generating a few Watts to generating several KiloWatts for the industrial turbines.

2.5.2 Active Solar

Active solar energy typically consists of solar panel usage. Commercial solar panels have been utilized since 1956, however only recently became a viable source of energy for homes and products. Today, you can typically see solar panels atop roofs, in calculators and as part of green initiatives to remove gasoline dependance from cars (Reece 2017). In this project, we will be focusing on solar panels that can be specifically leveraged to meet the energy demands of a typical Nigerian family.

2.5.3 Passive Solar

Passive solar is a largely underestimated energy source in building design. It has a wide variety of definition depending on its application in the building design but for the purposes of this project, passive solar is a source of energy derived solely from the heating action of the sun on the house.

Passive solar energy design is largely utilized in regions of fairly large temperature differences for keeping the house warm during the day and cool at night. A lot of the focus of passive solar design is the placement of the building’s windows, insulation and ventilation to cut down the energy needs of the project. While those are important factors for a successful passive solar design, this paper is going to focus on heat energy storage through the walls of a building in order to passively regulated the internal temperature of the house. The heat energy is stored during the day and released a night. Including this form of energy in the building design is an innovative yet low cost way of expanding on affordable and sustainable building design.

2.6 Building Materials

Building materials play an important role in modern technology. Approximately 70% of building cost goes into the building materials (Okwo 2006). The building materials industry is also an important contributor in our national economy as its output governs both the rate and the quality of construction work. There are great variety of requirements and usage placed on building there a multitudes of materials used; steel, concrete, cement, wood, rock, glass, etc.The environmental demand placed on building materials require a wide range of properties to be tested in various conditions such as a rapid change in temperature, stress relaxation, their resistance to water, acid and alkalis etc. The properties of the materials are predetermine for their applications as rational choice require comprehensive knowledge on the materials behavior on different conditions (Duggal 2017). There is a need for standardization for these materials as the quality must be consistent to avoid unpredictable failures. American Society for Testing and Materials (ASTM) Construction Standard has various methods and procedures to test various material properties. American Society of Civil Engineers has also published many standards on building materials.

Alternative building materials are being researched to decrease cost, pollution and their availability world-wide when compared to traditional material such as steel and concrete. Kabiru Mustapha tested the strength and fracture toughness of an earth-based natural-fiber reinforced composite. The material was a mixture of laterite, clay, cement, and straw fibers. The experiment was performed in Nigeria and materials were locally attained. The material was proving to have adequate properties to be used as a building material.

2.7 Clean Water

As important as the physical housing unit and energy system is, another key aspect of reliable infrastructure is access to clean water. Water is needed for anything from personal consumption to sanitation, but access to a reliable source of clean water is not as common as it should be. Unfortunately, many developing countries suffer from a water crisis. According to the World Health Organization, “2.1 billion people globally lack safe water at home” (WHO, 2015).

To put things into perspective, this is roughly 1 out of every 9 people in the world. Clean water that is usable for drinking water is referred to as potable water. This means that it is free of any harmful contaminants and suitable for consumption, but may also be used for other purposes as well.

Water scarcity has a negative impact on a global scale and can affect the entire well being of a region. For one, it introduces a health concern. A lack of safe water can lead to the spread of infectious diseases. Limited access to water also stunts the growth of a nation because time and energy must be used to collect water and transport it through inefficient means such as walking. Time spent collecting water takes away from time that could be used to work, go to school, or care for a family. If there was more access to water in the world, breaking the cycle of poverty would be a much easier task.

2.7.1 Rainwater Harvesting

Rainfall feeds rivers, lakes, and groundwater. These are all secondary sources on which humans depend for their water needs. A primary source of water, rainwater, is often overlooked and has untapped potential in many parts of the world. Rainwater collection takes advantage of natural precipitation and given the right climate, is a very sustainable source of water. Rainwater harvesting systems are most commonly found in agricultural irrigation practices and residential areas around the world (Kinkade-Levario, 2007). However, there are countries around the world that currently use rainwater harvesting systems for the purpose of capturing drinkable water.

The basic components of a rainwater harvesting system include a catchment surface, a conveyance system such as piping, some sort of filtration, a storage tank, and finally, a way to distribute the filtered water. Using the right materials, a rainwater harvesting system can be a simple and affordable solution to providing a source of clean water.

2.7.2 Water Filtration

Although, three-quarters of the earth's surface is water, only one percent of that water is available for human consumption (Oparka, 2010). As small of a percentage this is, there are still microorganisms that can cause life threatening diseases directly related to water.

Around the world, there are several ways to remove contaminants and purify water. Some of the technologies that remove large contaminants include screens, baskets, and basic sediment traps. To remove smaller, finer particles, microporous structures must be used. Finally, the water must be disinfected to rid it of any harmful microorganisms. There are three ways that water can be disinfected including the use of heat, chemicals, or light. More specifically, water can be boiled, can be treated with chemicals acting as disinfectants, and can be treated with ultraviolet light. For chemical disinfection of water, the following disinfectants can be used: chlorine (Cl2); chlorine dioxide (ClO2); hypochlorite (OCl^{-}); ozone (O3); halogens: bromine (Br2), iodine (I), bromine chloride (BrCl); metals: copper (Cu2+), silver (Ag+); kaliumpermanganat (KMnO4); phenols; alcohols; kwartair ammonium salts; hydrogen peroxide; several acids and bases (Oparka, 2010). Of the three main methods to disinfect water, the use of chemicals is the most common.

2.8 Location

Lagos, Nigeria is our select location. Nigeria is a developing country with a population of approximately 200 Million people. About 700,000 additional housing units are required annually, but only 100 units are produced yearly (Iwela 2014). About 80% of Nigeria population lives in inadequate and informal housing; which are poor quality, lack security of tenure and lack basic infrastructural facilities such as portable water and good sanitary systems (FGN 2009). There has resulted in slums such as Makoko (Fig 1).

Figure 0: Slums in Lagos, Nigeria 'Makoko'

The selection was based on recommendation for our advisor. Land between Aja and Epe has proven to be a prime locations for community development due to the economic upswing of nearby territory such as Eti-Osa. Figure 2 shows the area of land available for development.

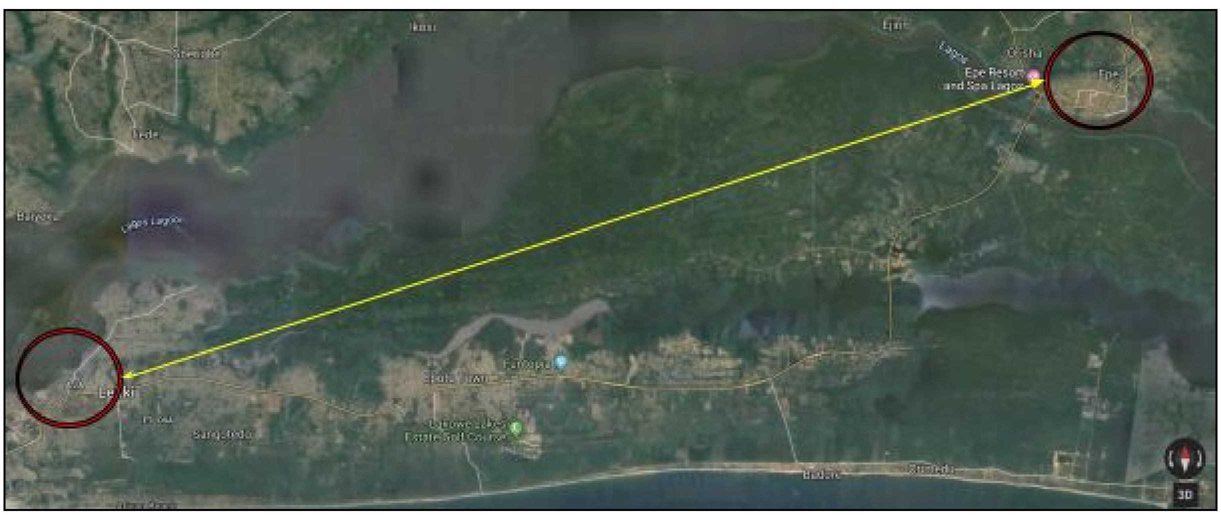


Figure 1: Map of Aja and Epe, Lagos Nigeria

2.9 Scope of Work

Our project looks to tackle a major global issue. To build a system that will be able to be applied anywhere in the world and at varying income levels, we incorporated a three-tier system - low, moderate, and upper class. By creating this were able to accomplish our goal of providing affordable and sustainable housing to everyone, regardless of social standing. The Managing Director of Federal Mortgage Bank of Nigeria (FMBN) estimates the housing deficit is between 17-20 million units, increasing annually by 900,000 units (Bah, Faye, Geh, 2018). This is especially important because Lagos, Nigeria is a developing country with 67% of its residents living below the national poverty line, this accounts for roughly 133 million people living in poverty. More than half of of Nigeria's estimated population live on less than U.S. $1 a day, the unemployment rate increased from 10.4% to 18.8% in 2017, and the minimum wage has remained constant for the past six years, even with an increasing inflation rate (Bah, Faye, Geh, 2018).

3.0 Building Materials

This chapter provides a brief overview of the use of building material. This primarily includes the selection of alternative building materials such as clay, laterite and sandwich panels. The materials thermal and mechanical properties were compared to traditional building material

3.1 Material Selection

There are various building materials used across the world; steel, concrete, cement, wood, rock, glass, etc. This is due to varying reasons in building design, building use, social and cultural impact, climate, location, and abundance of this material. But, a major governing factor in deciding what building materials fit into the affordable housing initiative is cost.

Approximately 70% of building cost goes into the building materials (Okwo 2006). This makes material selection an important aspect of design and construction development. A problem that many developing countries face is the application of relatively expensive cementitious building materials for building design. As a result, it is too expensive for people of low income to afford adequate homes. In other to bridge this gap, alternative building materials that are cheaper than cementitious materials are being test and implemented (Okwo, 2006).

The environmental demand placed on building materials require a wide range of properties to be tested in various conditions such as a rapid change in temperature, stress relaxation, their resistance to fire, water, acid and alkalis etc. Recent studies have shown that reinforcement of laterite with cement and natural fibers creates a building material with favorable mechanical properties (flexural strength, compression strength, fracture toughness) than that of cementitious materials. Meaning these materials can serve as sustainable and affordable alternatives to building materials. In an attempt to validate the properties of these new materials, mechanical tests were performed. These materials are intended to be utilized for the outer walls of the house. Unfortunately, due to lack of access to laterite and straw, we decided to explore a mixture of clay and cement as the building materials.

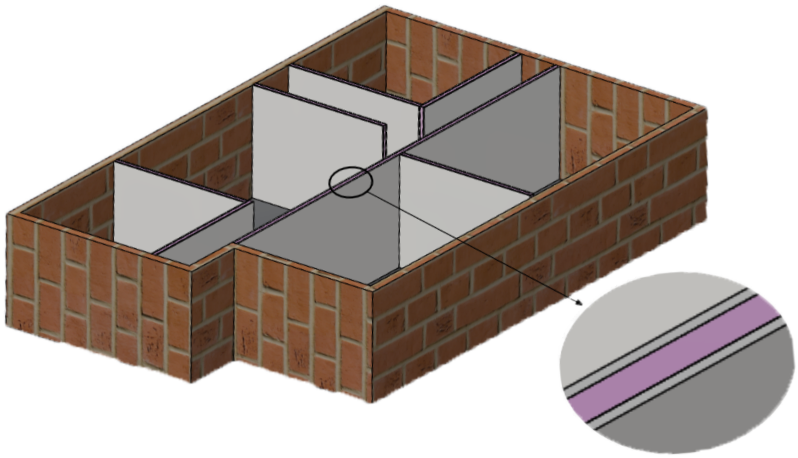


Figure 2: Wall Concept

Keeping to the trend of lowering building cost and utilizing sustainable materials, we explored the application of sandwich panels for the inner walls. Sandwich panels applications have been around since the 15th century, but in the last 40 years, they have gained popularity in building wall design. This is due to reasons such as the use of recyclable products, prevention in mildew growth, stable, inexpensive, good insulating properties, and high R-value. The application of sandwich walls to the affordable sustainable housing initiative a viable option.

3.1.1 Clay/Cement Mixture

The clay and cement in this work were obtained from Home Depot. The cement served as a binder while the clay served as the main component of the blocks making up a majority of the volume percentage. Clay was chosen because of its excellent mechanical properties and its abundance in Nigeria. This also leads to lower construction costs and better thermal insulation properties than cement (leading to lower energy cost) among others. The cement used was procured from Home Depot.

Preparation:

The brick comprised of a mixture of clay and cement at two volume percentages: 70% clay 30% cement (70/30) and 80% clay 20% cement (80/20). The mass of the clay and cement were determined using their respective density and the volume of the brick. The materials were dry mixed using a mechanical mixer to allow for an even distribution of each composition and were followed by the addition of water at a water-cement ratio of 0.3-0.5. The samples were prepared in a 2" cube mold manually with the aid of a hand trowel. The samples were cured for 28 days in the lab.

3.1.2 Sandwich Panel

Design

Sandwich panels are made up of three layers: two thin face sheet, and a low density core. Commonly used core materials include: foam, balsa, honeycomb, newspaper pulp and other recyclable materials. This provides and inexpensive light weight structure, while the thickness provides bending stiffness. The face sheet is commonly made with metals such as aluminum, steel, and zinc. However, other materials that can be used include: glass fiber, plywood, cement board etc. The face sheet provides resistance to tension and compression forces, durability and resistance to external forces such as weather. The core is attached to the face sheet using an adhesive or by brazing metal components together.

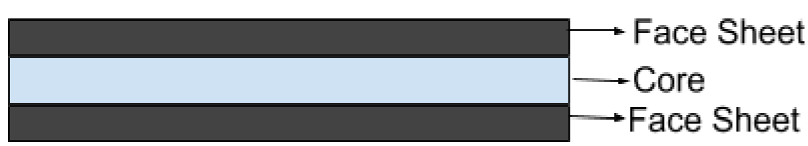


Figure 3. Sandwich Panel Design

For the purposes of this project, Aluminum will be used as the face sheet, pink foam will be used as the core material and epoxy will be used as the adhesive.

Fig 4. Sandwich Panel

Material Choice

As mentioned earlier, sandwich panels are have two main parts: the facesheet and the core. For this application, the facesheet was made out of Aluminum and the core material was polystyrene. Aluminum was selected because of it possess the following characteristics: light weight, non rusting, cheap, and accessibility. Polystyrene is cheap, recyclable with excellence insulation properties and available in abundance in Nigeria.

Failure

The sandwich panel can fail in a number of ways. These include:

- Facesheet: tension, compression, shear or buckling
- Core: shear or crushing

The facesheet and core could also be separated due to stress or shear on adhesive holding them together. These modes of failure determine the necessary tests for the sandwich panel. Due to time constraints and accessibility to adequate machines, we focused testing on the three point flexural test and the compressive test which is discussed in the next section.

3.2 Methodology

This chapter details all objectives and testing methods regarding building materials and passive solar testing.

3.2.1 Thermal Test

The overall objective of thermal testing is to identify the thickness of the outer wall which can absorb and store 12 hours of thermal energy from the sun. The clay/cement mixtures (70/30 and 80/20) thermal properties will be tested and determine using the following methods:

1. Guarded Longitudinal Comparative Calorimeter (GLCC)

2. Differential Scanning Calorimetry (DSC)

To determine the thermal conductivity of our clay/cement mixtures, the guarded longitudinal comparative calorimeter technique was used. A temperature gradient is created by a cooling plate with adjustable temperature profile and an array of temperature sensors that are recorded at different points. The is placed in a ‘sample stack’ between two Pyroceram 9606 meter bars of known thermal conductivity.

The sample stack is insulated with rigid expanded polystyrene to prevent lateral heat loss to the environment and ensure unidirectional heat flow. A more informative description is provided in another study. This technique follows the ASTM standard methods of D5470-06 and E1223-09.

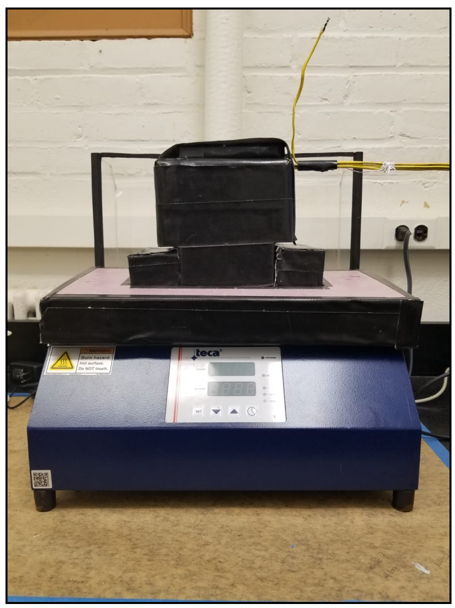


Figure 5: GLCC Method

The cold plate was cooled at a rate of 4ºC/h over 12.5 hr with a target temperature of -25ºC. The temperature was kept constant for 2 hr to allow the sample to reach thermal equilibrium. The temperature was then increased by a rate of 8ºC/h within 6.5 hr. This temperature profile was arbitrarily selected and was intended to display general behavior. Two inches cube samples were tested and the Pyroceram 9609 has a dimension of 1 x 2 x 2 in. The heat sink used is a thermoelectric cold plate (AHP-1200 DCP, TECA Corp). A USB data acquisition system connected with 16 gauge insulated type K thermocouples were used.

The thermal conductivity of our reference material (Pyroceram 9609) can be calculated by the following function:

$$\lambda_{pc} = -0.0061(T) + 4.2013 \ (-50\,^{o}C < T < 30\,^{o}C)$$

Where λ_{pc} is the thermal conductivity and T is the temperature. The information about Pyroceram 9609 is provided in another study. Equations from ASTM standard D5470-11 were used to calculate the average heat flow through the sample. λs and Q can be calculated using the following equations:

$$Q_{12} = \frac{\lambda_{pc} * (T_2 - T_1)}{d_{pc}} * A$$

$$Q_{34} = \frac{\lambda_{pc} * (T_4 - T_3)}{d_{pc}} * A$$

$$\lambda_s = \frac{(Q_{12} + Q_{34}) d_s}{2A(T_3 - T_2)}$$

In which Q_{12} and Q_{34} are the heat flow between lower meter bar and upper meter bar respectively; A is the cross-sectional area of the sample; d_s and d_{pc} are the thickness of the sample and the thickness of Pyroceram 9609; $\lambda_s$is the thermal conductivity of our sample.

To determine the specific heat capacity of our clay/cement mixtures, the differential scanning calorimetry (DSC) technique was used. The DSC is a thermoanalytical method in which the amount of thermal energy required to increase the temperature of a specimen being tested and a reference material is measured as a function of temperature. The specimen and the reference materials are kept at approximately the same temperature for the duration of the experiment.

The machine used for this experiment was the Netzsch 214 Polyma (Figure 6). It was connected to a software called Netzsch-Proteus-70 where all the data was collected. The clay/cement samples were grinded into powder form an put in an Aluminum pan crucible. Both the sample and the reference materials were loaded into the Netzsch 214 Polyma to begin testing; each sample weighed between 10mg and 20mg. The reference material used was an empty Aluminum pan crucible with a pierced lid. The experiment ran for approximately thirty minutes with a heating rate of 20K/min and temperature range from 20℃ to 600℃. We ran three experiments for each clay/cement mixture. The Data Charts can be found in Appendix D.

Figure 6: The Netzsch 214 Polyma

From our GLCC and DSC results, thermal diffusivity can be calculated using the following equation:

$$\alpha = \frac{\lambda_s}{\rho * c_p}$$

To the determine the thickness of the outer wall based on the diffusivity rate and time (6 Sun hour) the following equation is used:

$$x = \sqrt{2\alpha t}$$

3.2.2 Mechanical Testing

Clay/Cement Mixture

To determine the mechanical properties of our clay/cement mixtures, we ran two mechanical tests: three point flexure test and compression test. The three point flexural test was used determine the maximum stress that will cause the specimen to yield. The test was conducted on the Instron by loading the specimen on two supports separated by a distance, and then applying a force at approximately the center of the specimen. Each Specimen was 2” by 0.5” by 0.5’’. A total of 3 flexural tests was conducted. The setup can be found below in **Figure 1**.

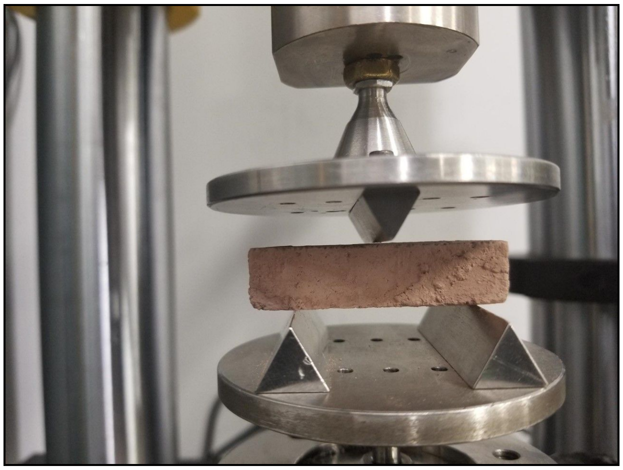


Figure 7. Three Point Flexure Test

Properties like the stiffness, yield strength, ultimate strength, resilience and toughness of the specimen is found using this test. The resulting flexural/bend strength (σ), was calculated using the formula:

$$\sigma = \frac{FL}{2bd^2}$$

where:

- F is the load applied to the specimen
- L is the length of the support span
- b is width of the specimen
- d is thickness of the specimen

The compression test was used to determine the behavior of the clay/cement mixture under compressive load. The test is conducted by loading the specimen between two plates (with no sharp edges or pressure points), and the applying a load to the specimen by moving both plates together. The specimen is crushed/deformed due to the compressive load and the force required to crush/deform it is recorded. The setup can be found below in **Figure 8.**

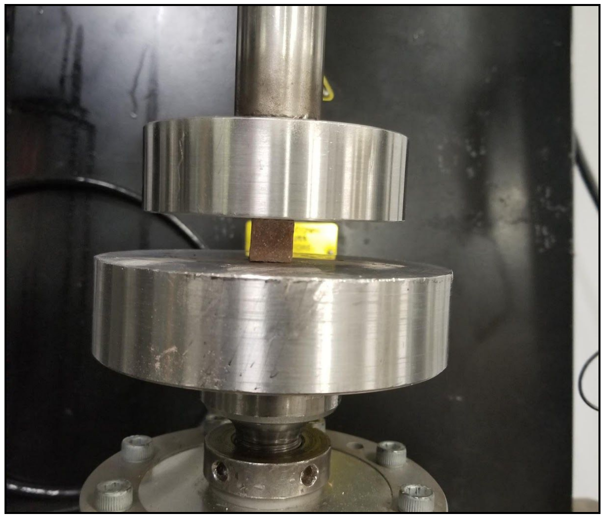


Figure 8: Compression Test

Properties like elastic limit, proportional limit, yield point, yield strength, and compressive strength are found using the compression test. The compressive strength of the specimen is calculated using the formula:

$$\sigma_c = \frac{F}{A}$$

where:

σ_c is the compressive strength

F is the force right before crushing

A is the area of the specimen

Sandwich Panel

To determine the flexural strength of the sandwich panel, we ran a three point flexure test. The three point flexural test was used determine the flexural stiffness of the panel, the tensile strengths of the face sheets, core shear strength and shear modulus. The test is conducted by loading the specimen on two supports separated by a distance, and then applying a force at approximately the center of the specimen. The setup can be found below in **Figure 9.**

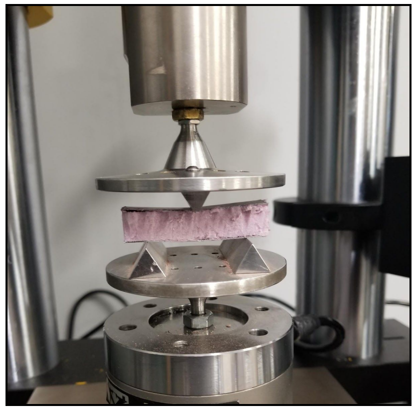


Figure 9: Three point flexure test setup

3.3 Results & Discussion

3.3.1 Passive Solar Capabilities

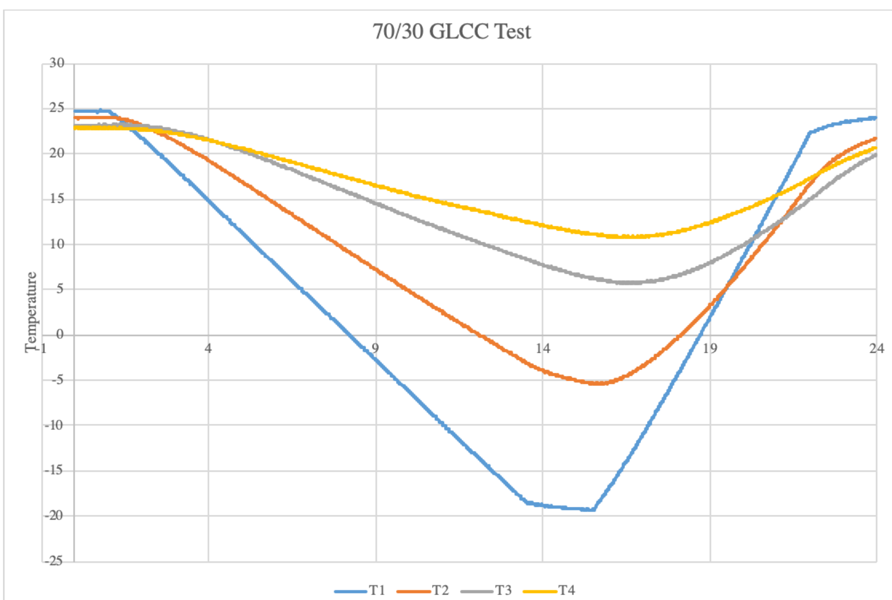


Figure 10: Results from 70/30 GLCC Experimentation

After getting the temperature points of the four sensor, Q_{12} and Q_{34} were calculated using the equation provide above and the thermal conductivity of the 70/30 clay mixture was determined to be 6.9 W/mK.

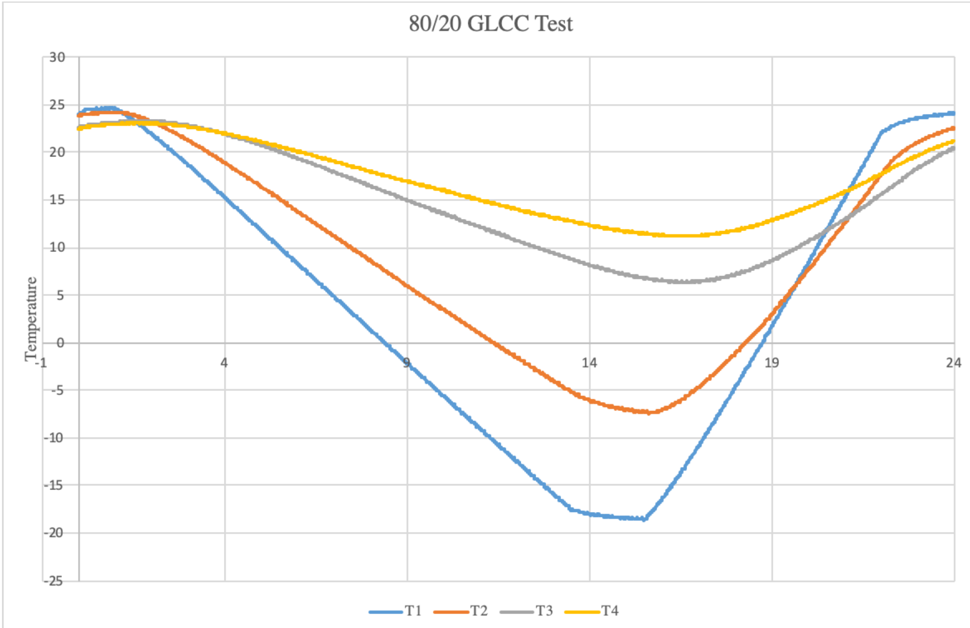


Figure 11: Results from 80/20 GLCC Experimentation

After getting the temperature points of the four sensor, Q_{12} and Q_{34} were calculated using the equation provide above and the thermal conductivity of the 80/20 clay mixture is 4.1 W/mK.

From the DSC experiment, the average specific heat capacity of the 70/30 and 80/20 clay mixtures are 2.148J/(g*K) and 0.9562J/(g*K), respectively. Their individual densities are 1876000 g/m^2 and 1694000 g/m^2 . Using the density, heat capacity and thermal conductivity, the calculated thermal diffusivity is 0.000001712 m^2/s for the 70/30 bricks and 0.000001017 m^2/s for the 80/20 bricks.

Using the formula mentioned above, the wall thickness required to store 6 hours of sunlight in both the 70/30 and 80/20 clay/cement mixture is 0.272 m and 0.210 m respectively.

Summary

	70/30 Clay/Cement Mixture	80/20 Clay/Cement Mixture
Thermal Conductivity W/(m*K)	6.9	4.1
Specific Heat Capacity J/(g*K)	2.148	0.956
Density (g/m^2)	1876000	1694000
Thermal Diffusivity (m^2/s)	0.000001712	0.000001017
Wall Thickness (m)	0.272	0.21

Table 1: Summary of Thermal Experiment

3.3.2 Mechanical Results

The samples 70/30 sample were expected to have higher flexural and compressive strength than the 80/20 sample because of the higher volume percentage of cement present.

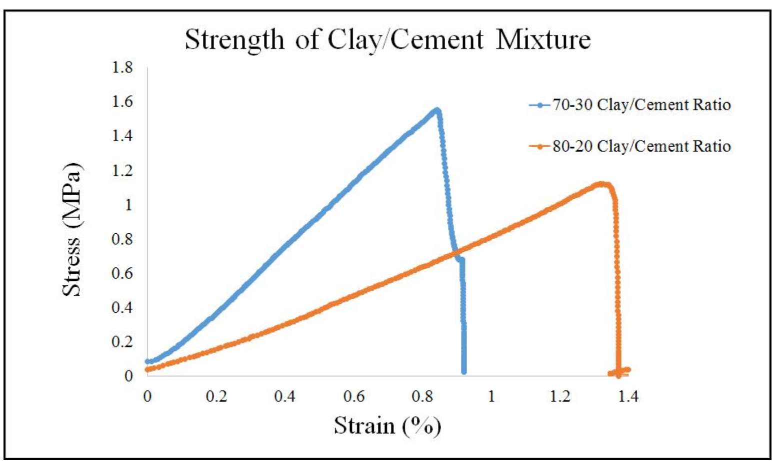


Figure 12: Strength of Clay/Cement Mixture Results

The results show that the 70/30 sample indeed had higher strength the 80/20 sample registering an average flexural strength of 1.6MPa and 1.2MPa. The average compressive strength of 70/30 and 80/20 is 4.17MPa and 3.02MPa respectively (Figure 13). However, the 80/20 sample had greater strain values than the 70/30 sample registering an average maximum strain of 1.77% and 0.92% respectively. Therefore, the 80/20 sample. The sandwich panel exhibited lower strengths than the bricks recording a flexural strength. The sandwich panel exhibited lower strengths than the bricks recording a flexural strength of 1.81MPa.

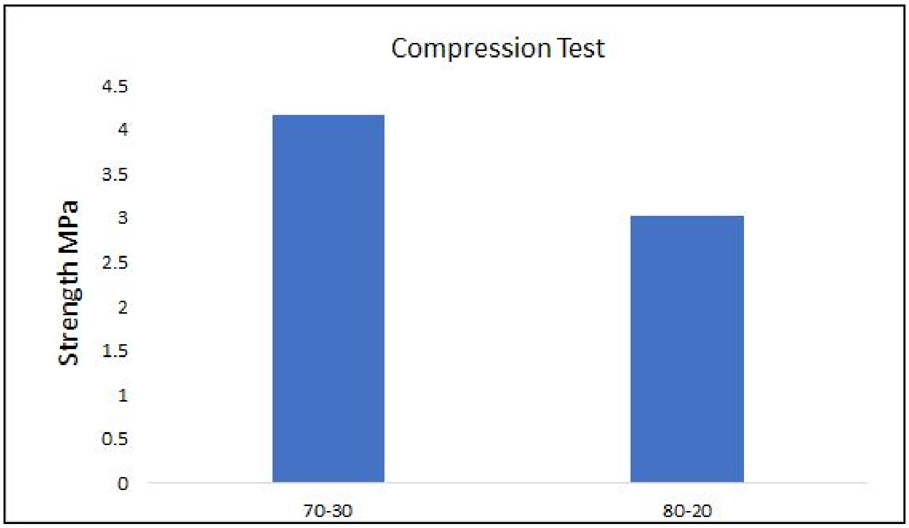


Figure 13: Compression Test Results

4.0 Energy

This chapter provides a brief overview of the energy aspect of the home. This primarily includes the wind turbine, solar panel, and wind turbine + solar panel - how they work, why they work, and how well they work in our design. Each technology will discuss the operational principles (theory) behind them and then discuss the methodology and results from testing.

4.1 Wind

Wind power has become more efficient in transferring kinetic energy to electrical energy. Conventional (tri-blade horizontal axis) wind turbines (in **Figure 14a** (Photo by Tom Corser)) are now designed in large scale and can be installed anywhere to collect sufficient energy. The efficiencies of these wind turbines are typically within 30-40% and are believed to generate the most electricity. These industrial wind turbines typically stand around 212 feet tall and have a rotor diameter of 116 feet. The industrial wind farms utilize such large turbines because the size of the wind turbine is directly proportional to the energy it's capable of generating. The relationship between the power and the wind velocity can be written by:

$$P=1/2\ \rho A v^3\ (\eta_\tau \eta_G) C_P$$

where P is the power of the wind turbine, ρ is the air density, A is the swept area, v is the wind velocity, C_P is the coefficient of performance, while η_τ and η_G are the wind turbine and generator efficiencies.

Another design that is commonly used as a water turbine is the Gorlov Helical Turbine (GHT) **(Figure 14b)**. By creating a cylindrical shape and adding a helical twist, the blades experience less torque pulse than on conventional tri-blade horizontal axis turbine. This in turn extends its expected lifetime. The turbine tested and integrated into this project is a GHT, created by Tan and co-workers (Johanson, Dao, Basch, O'Folan, Xia, & Tang, 2014). They created a self-sufficient campus lights by pairing this wind turbine with a solar panel to power lights around University of Vermont campus. Using 3-dimensionally printed joints, bamboo veneer and pipes, and a carbon fiber shaft, they were able to demonstrate the ability for this turbine to be made with renewable materials.

Figure 14a: Conventional wind turbine

Figure 14b: Gorlov wind turbine

4.1.1 Operation Principles

Wind turbines convert wind to electricity using aerospace, mechanical and engineering principles. To convert the wind to mechanical work, wind turbines use blades and pressure difference to rotate. Pressure difference is created by one side of the blade having a larger geometry than the other side. This difference in geometry means the air has to travel more distance to pass through the blade. This creates a low-pressure area over the larger geometry, compared to the high-pressure zone on the flat part of the blade. This pressure difference induces a force on the blade in the direction of high to low pressure (up in the diagram below). This force is what rotates the wind turbine, and thus rotates the electric motor producing electricity. This concept of air flow over a curved area is displayed in the below image.

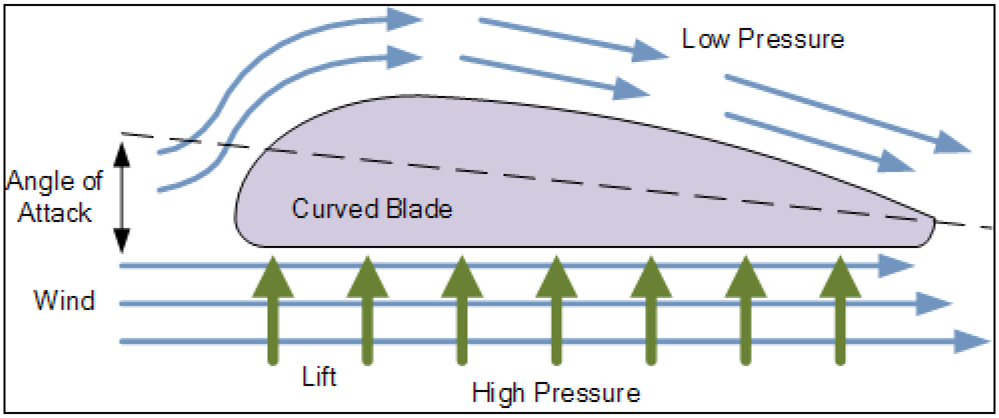


Figure 15: Wind Turbine Blade Design

Electric Motor:

The electric generator/motor is the component responsible for turning the mechanical work to electricity. A normal electric motor works by feeding it voltage and current and having the motor spin creating mechanical work from electrical. In wind turbines the opposite sequence of events occurs.

Electric motors have a few main components, the copper wiring, magnets, and the drive shaft. When you normally connect a motor to power, the current is sent through the copper wiring creating a magnetic field flux. This flux opposes the magnetic field created by the magnets in the housing and applies a force on the drive shaft, rotating it. When an electric motor is used in a wind turbine application, the wind forces the drive shaft to rotate, inducing a flux in the magnetic field and thus producing current. This can be seen in the image below, which also introduces the characterizing equation of $F = ILB$.

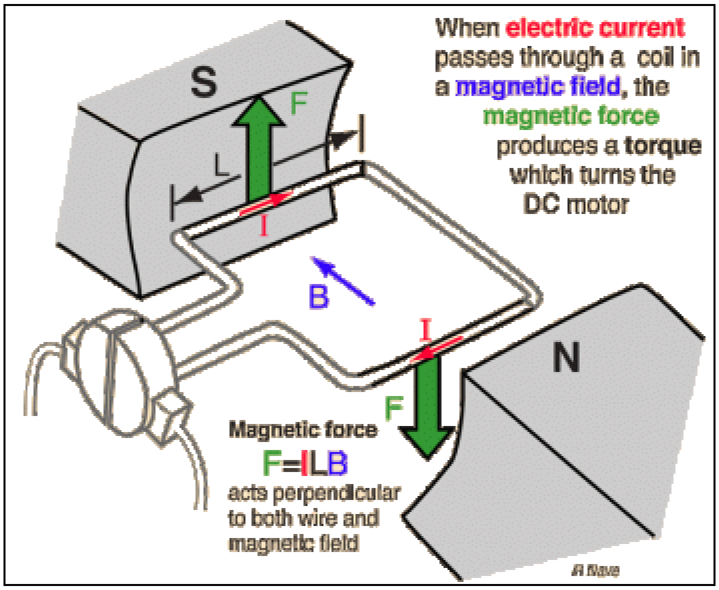


Figure 16: Physics in DC Motor

The equation F=ILB represents how you would theoretically calculate the force of the motor based on the current (I), the length of wire (L), and the magnetic field (B). Therefore, as you increase the force the current will increase, because the length of the wire and magnetic field are constant from the electric motor.

The Betz Limit:

The Betz limit is the theoretical maximum efficiency for generating power from the wind. In 1919, German physicist Albert Betz concluded that wind turbines are only able to transfer (at maximum) 59.3% of kinetic energy to electricity. In addition to this, Gorlov helical wind turbines have a maximum efficiency of 35% (Donev et al. 2018). This takes the total efficiency of the system down to 20.7% - in the ideal situation.

In realistic conditions there won't be constant enough wind to maintain the wind turbine and so there also exists a capacity factor.

Capacity Factor:

Each wind turbine has a specific power rating that represents the maximum output that turbine can generate. However, a turbine will not always generate that amount of energy because the wind power will not always be constant and at such high levels to always produce the maximum wattage of power. Therefore a capacity factor represents how much power the turbine will actually generate. The capacity factor is the average power generated, divided by the rated peak power (What does the capacity factor of wind mean? 2014). So if a 5MW turbine produces 2MW on average, then it has a 40% capacity factor.

4.1.2 Methodology

The objective of the following experiments is to evaluate the reliability and effectiveness of wind turbines as a means of energy production. This is important because we will be able to substantially improve their living conditions by providing electricity for appliances and amenities they couldn't afford prior. Before testing a housing for the turbine had to be designed and fabricated, this is the portion of turbine that houses the electrical motor and protects it from the elements, for our purposes it would also serve to stabilize it during testing.

Housing Design:

The main focus of designing a housing was to create something that would allow me to continue forward with the project and test the turbine. For this reason, the housing design took advantage of readily available parts. Its design is similar to those commonly found in the marketplace; turbine on top, an inline cylindrical housing that protects the motor and electrical equipment, and the support pole which would protect the wires and stabilize the turbine to the house (not fabricated because didn't need). The final housing can be seen below on the left, where as the housing created by the UVM students can be seen on the right. For the purposes of the homes, the design on the right would actually be implemented as it is a more robust system than the one created to test in this project.

Figure 17a: Our Turbine

Figure 17b: UVM Design

Wind Turbine and Battery Setup:

Wind turbine testing was done in the same environment using the same industrial fan every time to ensure consistent results. This attention to detail was echoed in the use of other materials in testing the capability of the turbine. Testing used a Ridgid Air Mover (AM2560), HoldPeak digital anemometer, Craftsman Multimeter (34-821411), and Lithonia Lighting 12-Volt 5 Amp battery.

First Experiment: Voltage vs. Wind Speed Test:

This was the primary test to model the amount of electricity the turbine would produce and at what wind speed. For this experiment, the turbine was connected directly to a multimeter on DC Voltage setting to read the voltage output. The fan was then brought in front of the turbine and its speed was found by using the anemometer. By moving the fan forward after allowing the turbine's voltage to climb and plateau, data and a resulting equation modeling wind speed and voltage was generated. This is an important relationship because it is a constant one, the turbine will always produce that amount of voltage at its corresponding wind speed.

Second Experiment: Current Testing:

The second experiment was to generate a model for the current generated by the turbine. When estimating the power generated by the turbine, the current is one of the most significant components. The following equation displays how to calculate power in watts, where P is power, I is current, and V is voltage.

$$P = I * V$$

For the experiment, two multimeters were used. One was connected in parallel to the output wires of the turbine, while the other was connected in series to the output wires of the turbine connected in series to a resistor of known resistance. By using the fan to spin the turbine, you are able to gather the data from both multimeters to generate data which results in a equation of current with voltage. From here we are able to estimate the yearly yield of the wind turbine, assuming perfect conditions and constant wind speed.

Third Experiment: Charging 12 Volt 5 Amp Battery:

This experiment was to determine how long it would take the wind turbine to charge a battery. For this we connected the turbine output wires directly to the battery terminals and ran the fan at a constant speed of 21 mph to mimic maximum wind speeds expected in Nigeria, as recorded by *Wind Speed Distribution and Characteristics in Nigeria by Adaramola and Oyewola* (Adaramola, 2011). The battery was first discharged down to 3.81 Volts prior to testing to allow for ample charging to occur. Every 10 minutes the battery was disconnected and voltage was recorded to generate a graph representing the charging of the battery over time. Through this experiment we found that the wind turbine would be unsuitable for 12 Volt battery charging by itself. This is because the wind turbine's voltage is based off the wind speed, and when the maximum average wind speed of Nigeria is around 21 mph, the wind turbine will be producing around 5 Volts at 2.5 Watts which won't charge the battery sufficiently as it cannot reach the maximum voltage of the battery. For this reason we knew to pair the wind turbine with the solar panel for maximum capability.

4.2 Solar

In 1956, the first solar cells were made commercially available for consumers. However, a typical 1W panel cost upwards of $300. This was far from attainable for an average consumer, so solar cells were mainly used as a novelty item in toys and radios. In the early 1960's, satellites in the Space Program were beginning to be powered by solar panels, and became the standard for powering space satellites. After this breakthrough, Exxon found a method to drastically reduce the price of solar cells down from $100 per watt to approximately $20 per watt. This research led to most oil rigs using solar power to power the lights on rigs. People began adapting solar panels for use in railroad crossings, homes and even telecommunication towers. They were especially prevalent in remote areas that did not have easy access to electricity except via long power cables that connected them to main city grids.

Through these advances, we now see solar panels being used in various creative ways. Solar powered cars and even homes powered solely through solar panels are becoming increasingly common. Recently, technology has allowed us to fabricate printed solar cells and solar fabric that can be used on the sides of homes. Solar shingles also can be installed on roofs to contribute further to the energy needs of a family (Reece 2017).

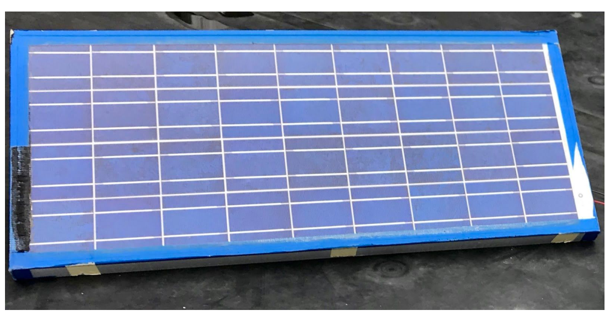


Figure 18: Solar Panel Used in Testing

4.2.1 Operational Principles

In order to gain fundamental knowledge of the reliability and viability of solar panels in a sustainable house model, we must first understand how a basic solar panel functions.

A solar panel functions by allowing photons to knock electrons free from atoms. This action generates electricity. To do this, solar panels use photovoltaic cells. Photovoltaic cells are made of materials called semiconductors. Silicon is the most common semiconducting material used in solar panels. Each photovoltaic cell is “sandwich” of two slices of that material. When light hits the cell, some of it is transferred to the silicon. That energy knocks electrons loose, as mentioned previously, allowing them to flow freely (Dhar 1).

To actually generate electricity, photovoltaic cells also need an electric field. To get this field, the semiconducting material is doped with other materials to give each slice of the “sandwich” a positive or negative charge. To make knocked electrons into useable electricity, solar panels use metal conductive plates on each side of the cell collect the electrons and transfer them to wires. At that point, the electrons can flow like any other source of electricity. This current, together with the cell's voltage, defines the wattage, or power, the solar cell can produce. (Dhar 1).

With this understanding of solar panels, we can being to see that solar panels are may be viable in a Nigerian setting. Nigeria’s average solar insolation ranges from 4.0-4.9, which is overall extremely high compared to the rest of the world (Marvin 2012). This high solar insolation over a typical 5 - 6 sun hour day allows for a higher panel efficiency in Nigeria than other places in the world. Subsequently, this also allows for a very high energy output from a solar panel in Nigeria and shows promise in being able to provide enough energy for the needs of a typical lower-income Nigerian family.

4.2.2 Methodology

The objective of the following experiments is to validate that solar panels are a reliable means of energy production for the typical Nigerian family. This is important because, by being able to provide low-income Nigerian families with electricity, we will be substantially raising their living standard and providing them with consistent energy capable of meeting their energy demands.

Solar Panel & Battery Setup:

In these experiments, we tested using 2 5W solar panels and 4 6V, 4.5A batteries. We also used a large 60 W panel for additional testing. We connected the 2 5W panels in series for a total solar panel of 10W. We used an individual 5W panel and a single 6V battery system to simulate a lower income energy situation. We used the 2 5W panels and 4 6V batteries to simulate a low - middle income energy situation.

We connected the batteries in 2 sets. A single set comprised of 2 6V batteries connected in series, and the two sets were connected in parallel for a cumulative "battery" of approximately 12V, 9A. The total capacity of this battery system was 108 Wh, or .108 kWh. We set the 4 batteries up like this, and not all in series, because setting them up in series would yield too large a capacity for the purposes of our experiments. We utilized a multimeter to confirm this.

To ensure that current was properly traveling from the solar panels into the battery, we utilized a central charge controller between the wires of the panel and the wires of the battery. The charge controller served as a mediary between the two where the positive and negative terminals of each were connected to their respective ports in the charge controller. This allowed current to safely pass from the panels to the battery and give us accurate current and voltage readings off of the multimeter.

We performed experiments under the assumption that never wanted to fully drain the battery. This gave us a healthy reserve of energy to work with in the battery, and increased the overall longevity of the battery. With longevity in mind, we also fully charged battery between tests if the test didn't already fully charge the battery.

Battery Preparation:

In order to maintain the integrity of the battery, we ensured that the battery was fully charged to near its full capacity after each test. We achieved this by exposing the solar panels to two 500W floodlights and waiting until the batteries were fully charged. Then, we safely discharged the batteries to approximately 15-33% capacity.

To discharge the batteries, we connected two 12V, 3.5W light bulbs in parallel to the battery. We kept track of the battery voltage using a multimeter while the light bulbs were connected to the battery.

Testing:

These are the 2 main tests we performed to validate the reliability of solar panels as a means of energy production:

1. Testing Under Simulated Conditions

The objective of these tests was to simulate perfect sun exposure for our solar panel - battery system. This allowed us to see, under absolutely perfect conditions, the maximum energy our solar system can produce in a typical 12 sun hour window.

To test ideal conditions, we first followed the initial battery setup and preparation procedure. Then, we set up our solar panel/battery system underneath two 500W flood lights to simulate 1 sun exposure (1000 W/m^2). We then tested to see how long it takes the solar panel to fully charge the battery from our aforementioned 30% starting charge. The solar panel was set at a 40^0 angle directly underneath the floodlights for 5 consecutive hours. This ensured that the current output of the solar panel is maximized for proper comparison to other tests, and that the setup accurately reflected approximately 12 sun hours of light exposure.

Voltage and current readings were taken every hour on the hour and recorded. Afterwards, an average power gain in the battery over the 5 hours was calculated using the equation P = V*I where P is power in watts, V is voltage in volts and I is current in amps. From these experiments we expected that, in 5 hours, our battery will be fully charged seeing as they will have total sun coverage for 5 hours, fully charging the battery to its maximum capacity. This would confirm that solar panels are a valid source of energy in perfect conditions.

2. Testing Under Realistic Conditions

The objective of these tests was to understand the reliability of solar panels during different weather conditions, and thus different levels of sun exposure. This allowed us to fully understand the realistic capabilities of small-scale solar energy for our house. To test actual exposure to solar irradiation, we first followed our initial battery setup and preparation procedure. Then, we set up the solar panel outside during 3 different classified days:

a. Clear/sunny. This weather is closest to the ideal weather for the solar panel. This weather is characterized with little to no clouds in the sky and direct access to sunlight during a large majority of the time window.
b. Partly cloudy. This weather is not ideal, but still provides sunlight for the solar panel. This weather is characterized by multiple clouds in the sky, with enough clouds to block

out the sun for extended periods of time. However, the sun is not always blocked, and still exposes itself to the solar panel during a majority of the time window.

c. Cloudy/overcast. This is the least ideal weather for the solar panel, with little to no direct sun exposure at all throughout the day. This weather is characterized by clouds completely covering the sky and blocking out the sun for a large majority of the time window.

These days were determined in advance to ensure appropriate testing. These tests were done in Worcester, MA during December when the average solar insolation during the month was approximately 1.3. The solar panels were set at a 45^{o} angle to maximize the current output of the panels for 5 consecutive hours from 11 AM to 4 PM during each day.

Voltage and current readings were taken every hour on the hour and recorded. Afterwards, an average power gain in the battery over the 5 hours was calculated using the equation P = V*I where P is power in watts, V is voltage in volts and I is current in amps. From these tests, we expected that cloudy weather would yield the lowest power gain, sunny weather would yield the greatest power gain, and partly cloudy would yield a power gain in between the two. We expected that solar panels will prove to be a viable source of energy in sunny and partly cloudy weather, but would prove to not be in cloudy weather.

Charge Test:

In addition to testing the viability of solar panels in different conditions, we also wanted to test to model the charging and discharging rate of our solar panel-battery system to confirm our results matched our subsequent conclusions. To do this, we decided to use our 60W panel and cumulative 12V battery under the floodlight to achieve an equation that modeled the best case scenario for our system. Utilizing two 500W floodlights, we took current measurements using a multimeter every hour as we were charging the battery. We then performed a simple Q = I*T calculation (where Q is charge, I is current and T is time), to find the charge generated or lost at any given time we measured current. Finally, we plotted charge as a function of time, where charge resides on the Y-axis and time on the X-axis to achieve a model for a charging and discharging rate.

Once we concluded charging tests, we also modeled the discharging rate of the battery. We utilized the same lights from previous experiments to discharge the battery, taking measurements every few minutes as the battery was discharging. Plotting results was identical to

The resulting equations gave us confirmation that our results and following conclusions were accurate by demonstrating that the charge gained at any particular time could be mapped to a specific time coordinate. This would show us that both our solar panel and battery were displaying correct results on our multimeter as we could relate our results to the real world where a typical day contains 10-12 sun hours (approximately double of what we test). We expected that, over 5 sun hours, the battery would have fully stored charge up to max capacity at a linear rate, and that the battery would have discharged similarly.

4.4 Wind + Solar

The objective of these experiments was to evaluate the reliability and effectiveness of combining solar and wind power together in one circuit. Additionally, we wanted to verify that it was possible to combine the voltage outputs from the solar panel setup and the wind turbine to yield a total greater voltage output. Finally, we wanted to design a unique circuit that would fully and properly leverage the wind turbine and solar panels to their optimum potential.

4.4.1 Methodology

In order to test the solar panel and wind turbine at the same time, we decided to find a large and open area where the wind turbine could run in its maximum wind speed environment. For our purposes, we also decided to utilize the 65W panel and two 500W flood lights instead of setting up the panels and turbine outside. This allowed us to maintain a more controlled environment for the wind turbine and a more controlled light source for the panel so that we could have consistency across both energy outputs. This consistency would simplify much of the math involved down to simple addition of our voltage outputs.

A majority of our results was not only assessing the voltage characteristics of the two energy sources working in tandem, but also the physical wiring of the two itself. In order to wire the two energy sources together, one cannot simply wire them in series directly to a battery. The issue with this is that the wind turbine will draw power directly from the solar panel and battery instead of outputting into the battery. This means that the battery and solar panel will begin to spin the wind turbine without any wind source.

To fix this issue, we connected the solar panel and wind turbine to their own separate charge controllers. This ensured that the current from the battery and panel would not flow back into the wind turbine. From the charge controllers, each was connected to a 12 Volt 5 Amp battery which were then connected in series, producing a 24 Volt potential difference. A diagram showing the wiring is shown below.

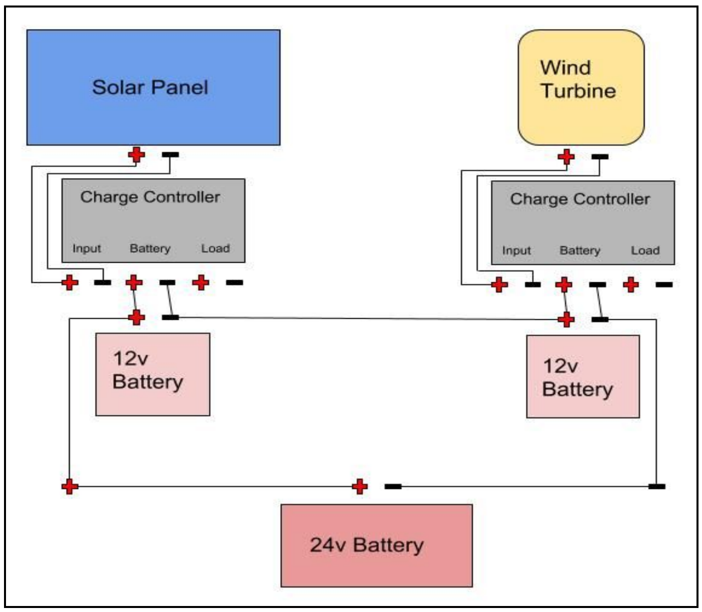


Figure 19: Wind + Solar Wiring Diagram

This test would serve as the primary reasoning for having both a wind turbine and solar panel for a home. The solar panel is capable of producing 65 Watts at 20 Volts, and the turbine is capable of producing nearly 2 Watts of power at 4 Volts, which means combined they should be able to power a 24 Volt battery system.

For this experiment we used the flood lights, solar panel, industrial fan, wind turbine, two of the 12 Volt 5 Amp batteries, two charge controllers, the multimeter, and anemometer. The solar panel was setup at a 45° angle to maximize its potential and the wind turbine was setup with a 21 mph wind speed to simulate the maximum average wind speed encountered in Nigeria, as previously described in the wind section. Testing was completed with intermittent measuring of the battery storage.

4.5 Results & Discussion

This section will take an in-depth analysis of the results from the experiments completed in the energy section. This includes the wind turbine, solar panel, wind turbine + solar panel, and passive solar results. Results from other sections will be found in respective sections.

4.5.1 Wind Results

First Experiment - Wind Speed vs. Voltage Testing:

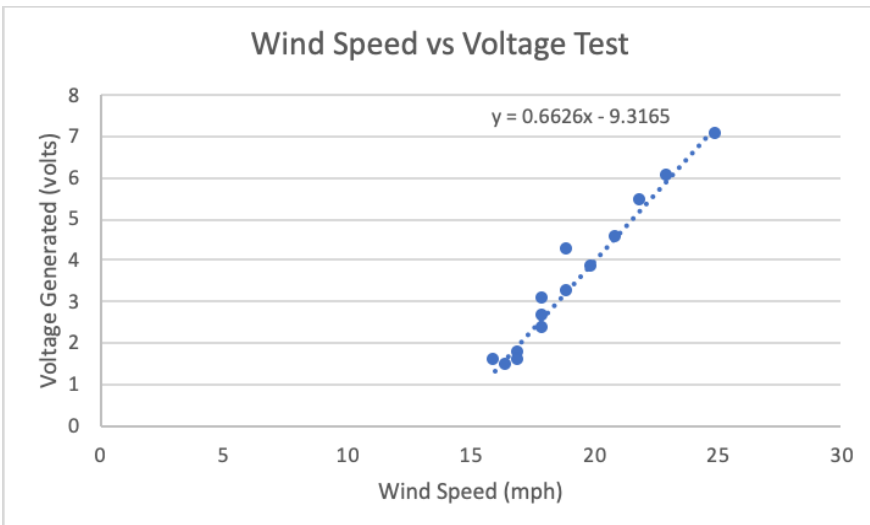


Figure 20: Wind Speed vs. Voltage Testing

After getting the turbine to a point where it was stable enough to be tested, the first experiment was to see how much voltage we could generate from it. Knowing that certain wind speeds correlate to certain voltage amount, the goal was to develop this relationship through equations generated through data. By conducting multiple tests to strengthen the correlation through data, the graph and equation presented above show the relationship of wind speed and voltage generated. Evident above, increasing wind speed results in increased voltage generation. It also supports the data presented in Dr. Ting Tan's report that the turbine's startup wind speed (wind speed at which the turbine will begin to create electricity) is around 16 mph.

Second Experiment - Current Testing with Resistor:

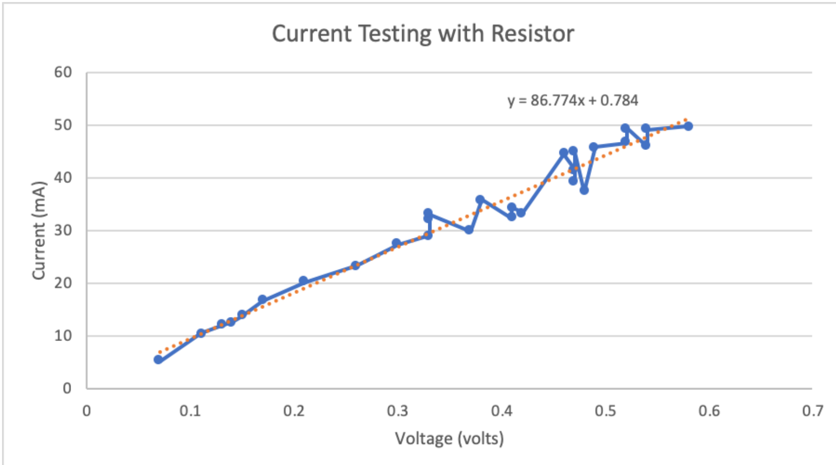


Figure 21: Current Testing with Resistor

After finding the relationship between the wind speed and the voltage generated by the turbine, the next step was finding the current produced by the turbine. Little data on this was given my Dr. Ting Tan's report, but using the specification sheet of the electric motor we knew the current generated would be low. Using the specification sheet of the motor, the full load current of the motor is 0.8 Amps. Full load amperage is the current amount produced at the rated voltage, and the rated voltage is 90 Volts DC. From these values we can compute the resistance of the motor using the equation below.

$$V / I = R$$

$$90 \text{ volts} / 0.8 \text{ amps} = 112.5 \text{ Ohms}$$

To confirm this, we completed this test using a 11.26 Ohm resistor, whereby the results are show above. Although a significant amount of current was not generated, if you estimate how much current would be produced using the motor resistance found, the results are confirmed, shown below.

$$V / R = I$$

$$0.3 \text{ volts} / 112.5 \text{ ohms} = 0.00267 \text{ amps}$$

This result of 0.00267 amps is exactly a factor of 10x off from the test results, because the resistor used was 10x smaller than the motor's resistance.

Third Experiment - Charging 12v 5000mAh battery:

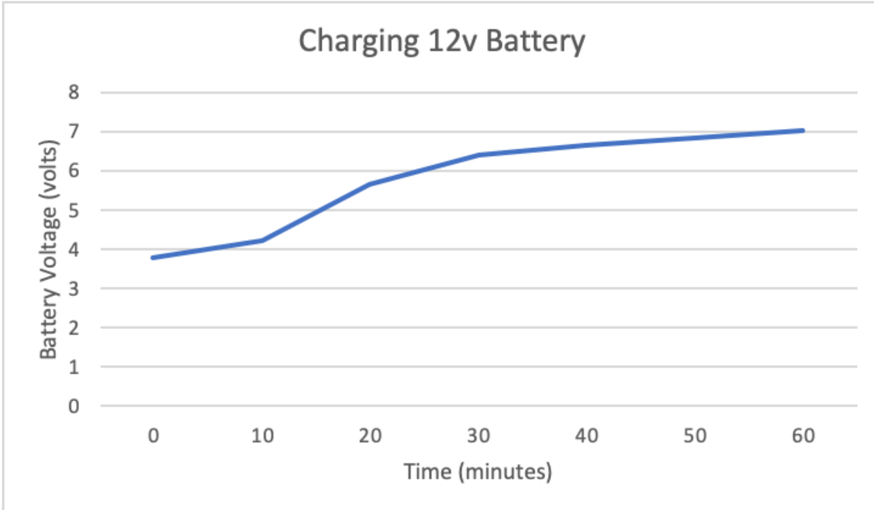


Figure 22: Charging 12V Battery

The source of electricity in our design will be the solar panels and wind turbine. To store this electricity we need a host of batteries to provide energy throughout the day. This test shows the charging characteristics using only the wind turbine. Evident by the graph is that because the wind turbine's voltage is dependant on the wind speed, the battery's voltage is only able to reach around 7 volts - as this was the voltage of the turbine

4.5.2 Solar Results

	Simulated	Sunny	Partly Cloudy	Cloudy
Starting Voltage	0V	3.92V	4.07V	4.6W
Ending Voltage	12.6V	11.95V	11.46V	11V
Voltage Gain	12.6V	8.03V	7.39V	6.4V
Average Power Gain	113.4W	72.27W	66.51W	57.6W
Time Elapsed	12 hours	5 hours	5 hours	5 hours

Table 2: Solar Weather Condition Test Results

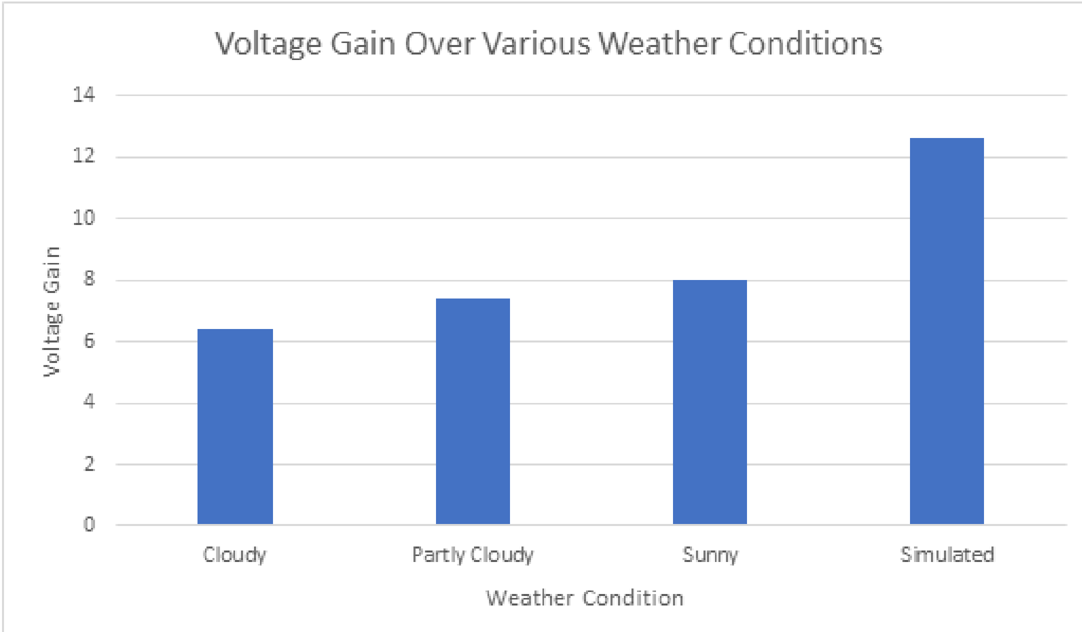


Figure 23: Solar Weather Conditions Test - Voltage Gain

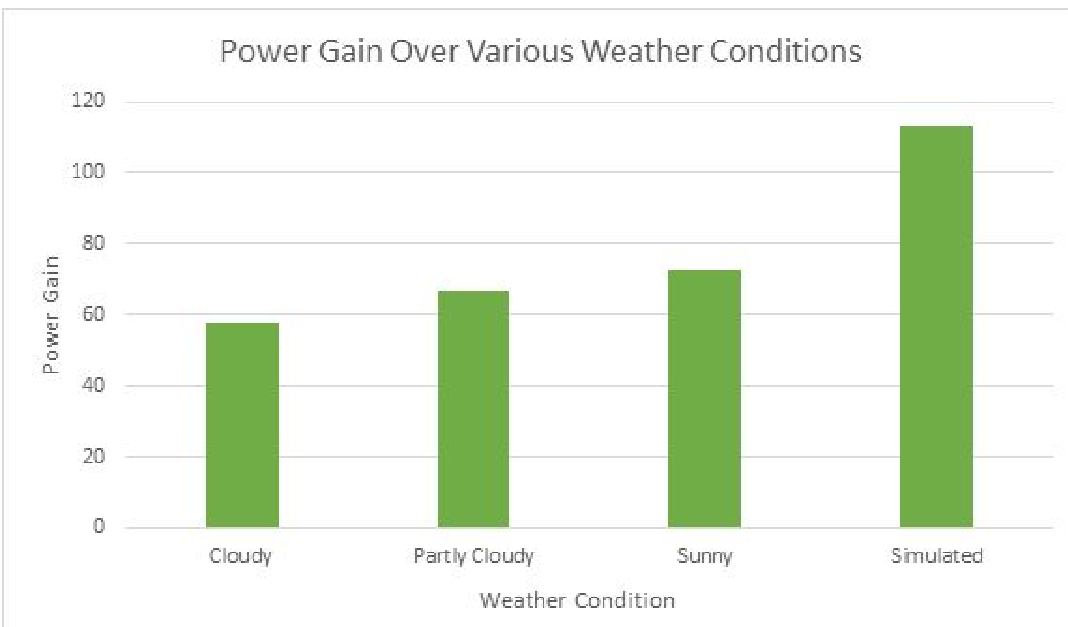


Figure 24: Solar Weather Conditions Test - Power Gain

The above graphs give a visual representation of the data collected over the aforementioned tests for simulated and realistic conditions. As expected, the data shows a notable increase in voltage and power as it became progressively sunnier per test. Our simulated condition test far exceeded our realistic condition tests. These results showed much initial promise for providing electricity to our home. The following graphs visually represent our charge test results:

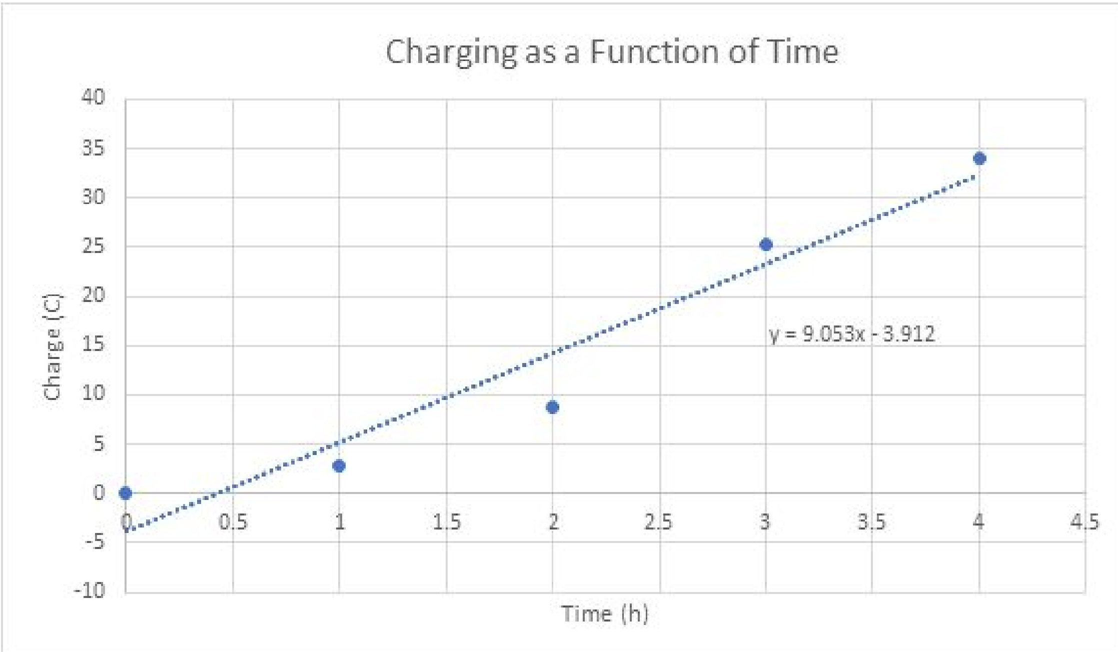


Figure 25: Solar Battery Test - Charging

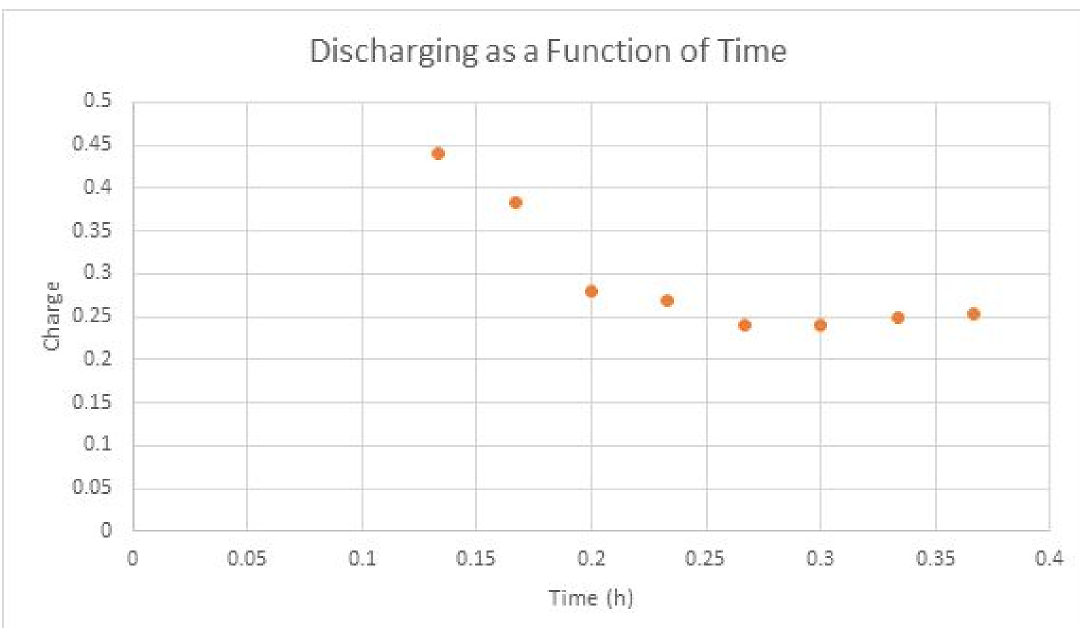


Figure 26: Solar Battery Test - Discharging

Our charging rate is linear, and our discharging rate is exponential. We decided to repeat this process for a 5W panel 6V battery setup to simulate a low income families energy needs. However, since we already had a discharging rate from our previous discharge model, we chose to only focus on a charging model for this scenario. The following graphs visually represent this setup's results:

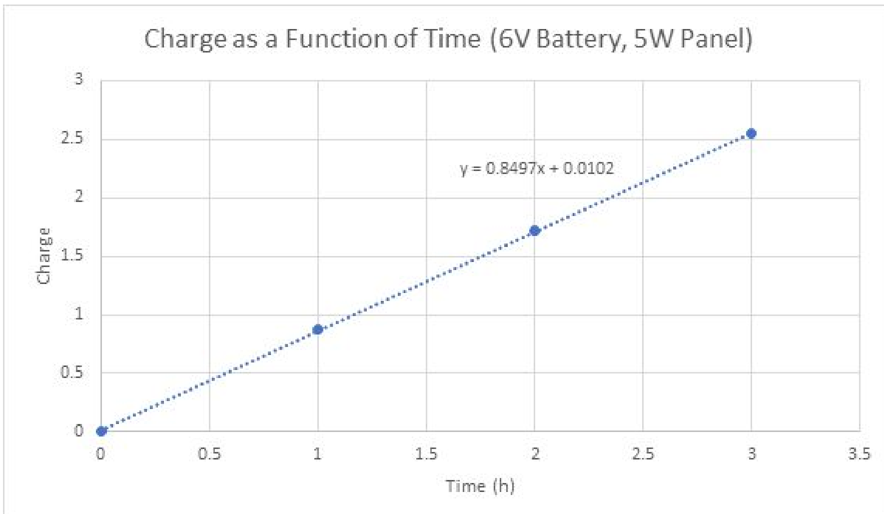


Figure 27: Solar 6V 5W Test - Charge over Time

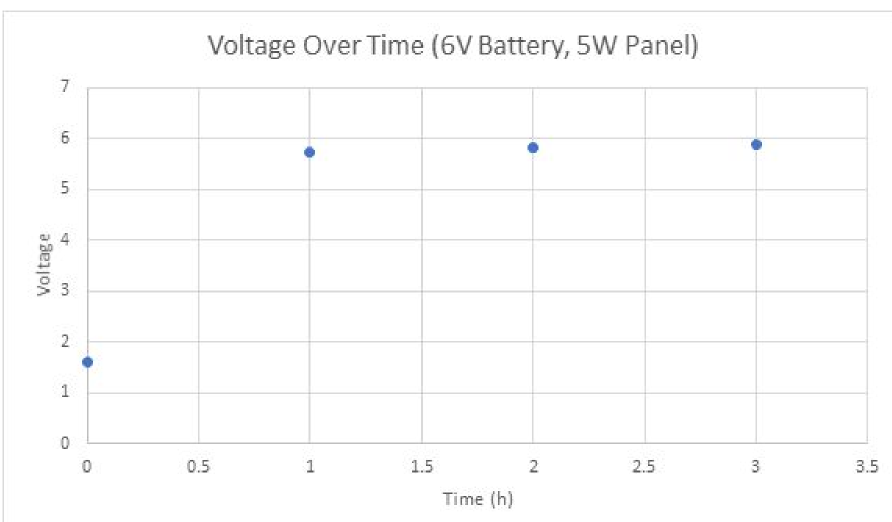


Figure 28: Solar 6V 5W Test - Charge over Time

Our charging rate is once again linear. This time, the single 6V battery was able to charge up much quicker compared to our original panel-battery setup. The charging rate was slightly lower, but due to the capacity being much lower, the battery was able to charge up quicker despite the lower charging rate and smaller panel wattage.

Analysis of Solar Results:

From our results, we conclude that solar is a more than viable option for energy generation. Every single one of our setups either met or exceeded our expectations for voltage, power and charge rate. In our initial simulated test, our solar panel setup was able to charge up out battery within 12 hours. This test in particular confirms the validity of the particular solar panels and batteries we were using because a typical day consists of 10-12 sun hours. In this "perfect" scenario we ran, we ended up achieving full charge on the battery within one full day of sun hours, which is precisely what should occur when using a cumulative 1000W light source on solar panels.

In our realistic tests, we found that, even in cloudy weather, our solar panel setup was able to adequately charge the battery in comparison to other weather conditions. In partly cloudy and sunny weather, within 5 hours the battery was charged up close to maximum capacity, with only slight variance in the total voltage gain per test. Additionally, as mentioned in our Methodology, these tests were done in Worcester, MA during December when solar insolation is at its lowest. On the contrary, Nigeria's solar insolation ranges from 4.0-4.9 w/m^2 and stays relatively consistent throughout the year. This means that our solar panel setup should charge even faster during a typical Nigerian day. This demonstrates that solar panels are extremely reliable sources of energy generation in varying weather conditions, especially within a Nigerian context.

Our charge tests confirmed the reliability of the results we achieved by creating a linear relationship between time and charge. This shows us that, with a consistent light input, solar panels can output a steady linear supply of power. Additionally, we cannot forget that the roof of our house is not limited to one or two solar panels. Our roofing is ~62 m^2, and depending on the income level of the family, we can tailor the size, wattage and amount of solar panels based on the respective energy needs of the family. Due to the nature of solar panels and the results of our charge tests, we know that this sort of tailoring to income level and energy needs is very possible for our home. This shows that our home is adaptable to the energy needs of varying degrees because of our aforementioned analysis that solar panels can easily and effectively provide constant electricity to our home within a 5 - 6 sun hour time period in both simulated and realistic conditions. In tandem with the wind turbine, this provides for an effective and efficient energy solution for our home.

4.5.3 Wind + Solar Results

From our individual wind and solar tests, we were able to establish that the wind turbine and solar panel can separately and successfully charge a 12V battery from low capacity. Theoretically, this meant that when we combine the two we should be able to charge a 24V battery.

The solar panel and wind turbine are connected to separate charge controllers as mentioned previously. These charge controllers are then connected to their own 12V batteries, which are connected in series to create an effective 24V potential difference. The circuit successfully creates a closed system where, when the solar panel is exposed to a light source (such as our floodlights) and our wind turbine is exposed to a wind source, the two outputs add together in series. This circuit is also specifically designed so that the current from the batteries and the solar panel do not travel backwards into the wind turbine.

Below is a representation of the voltage output from the joint wind and solar test:

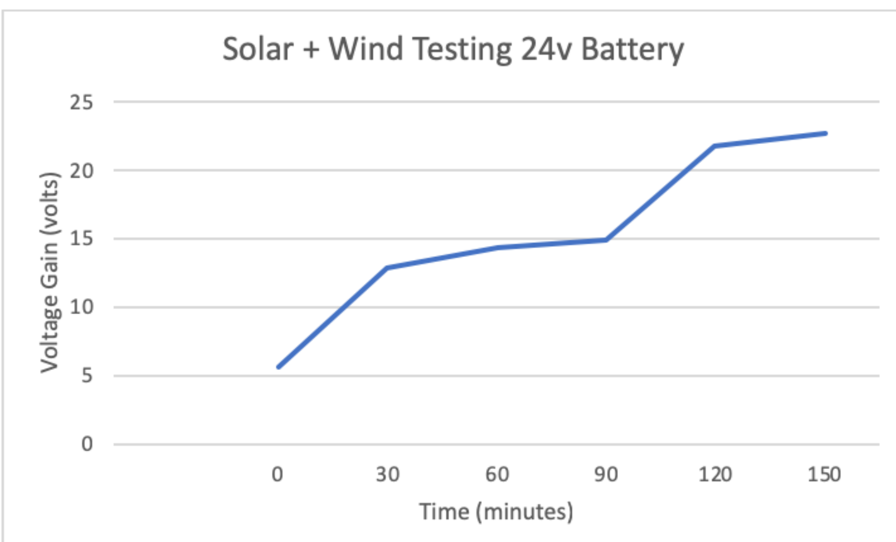


Figure 29: Solar + Wind Testing 24v Battery

As you can see, the voltage gain steadily increases over time, and can be seen to peak very close to 24V. This is very promising because our initial goal was to evaluate if the combined system could reliably charge a 24V battery. In approximately 2.5 hours, the 60W panel and wind turbine were able to charge the cumulative battery system fully. This proves that the circuit we designed is able to reliably charge our battery in a short amount of time. Since the solar panel was exposed to the floodlight, we must assume that the 2.5 hours is an underestimation of the realistic time it would take to fully charge a 24V battery in realistic conditions. However, based on our weather condition solar tests, we can safely assume that our will be able to charge 12V within 5 sun hours. Therefore, the total system will be able to fully charge within approximately 5 hours, with slight variance based on the weather condition.

5.0 Clean Water

This chapter provides a brief overview of how our design incorporates sustainable and affordable methods to provide clean water. This includes the basics of rainwater harvesting and how it is implemented into our design. In addition, the process of water filtration through ceramic filters is discussed as the water transitions in our system from contaminated water to potable water. The technology and mechanics of how these ceramic filters work is explained as well. The scalability of the water filtration is investigated and the results of these tests are discussed.

5.1 Rainwater Harvesting

Rainfall Trends in Nigeria:

By studying the annual rainfall trends of Nigeria, it is possible to determine the capabilities of a rainwater harvesting system incorporated into our design. As shown by **Figure 30** below, Nigeria's average annual rainfall is approximately 1,165 millimeters.

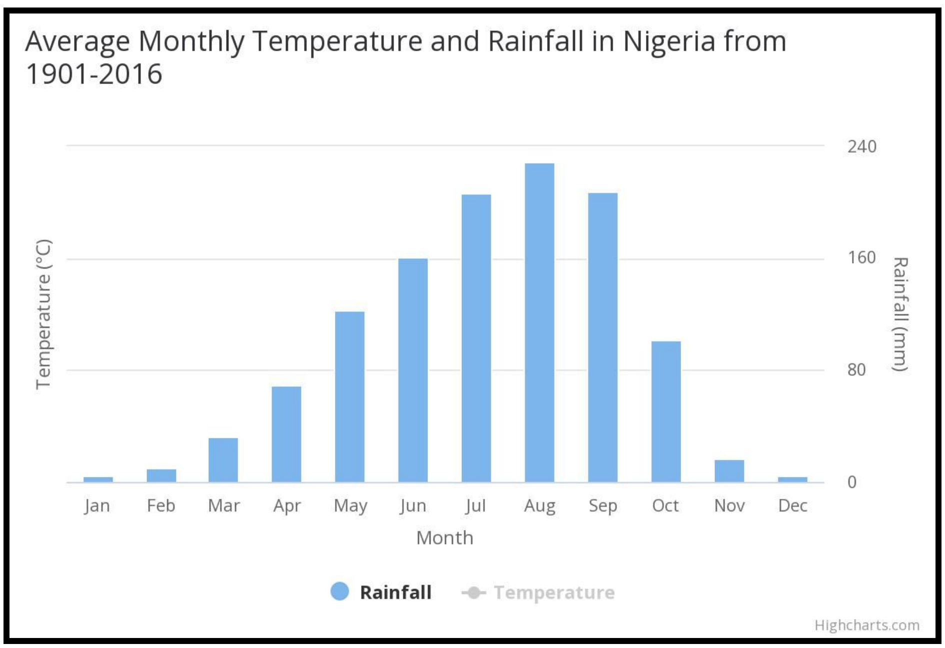


Figure 30: Annual Rainfall in Nigeria (1901-2016) (World Bank Group, 2018)

Our house design uses a roof footprint of just under 100 square meters of area that can be used as a catchment surface. According to the United Nations Environment Program, rooftop catchment efficiencies are typically about 75% of the actual rainfall on the catchment area, after accounting for losses due to evaporation (UNEP, 1997). Assuming there is 1 cm of rain and 100 square meters of roof, the yield has a potential of 1000 liters of water. Following these calculations, a 75% catchment efficiency, and incorporating Nigeria's rainfall trends from the last 115 years, we can calculate an average availability of 87,400 liters of rainfall captured by single house in Nigeria every year. This is the average for all of Nigeria, so the total water availability can fluctuate between regions experiencing higher or lower rainfall averages. Clearly, rainwater harvesting is capable of meeting the basic water requirement in Nigeria.

5.2 Water Filtration

5.2.1 Operation Principles

Ceramic Water Filters:

Clay can be found around the world at reasonable costs. In Nigeria, this resource is abundant and relatively easy to process. Studies have also shown efficient removal of microorganisms with the help of ceramic water filters in general. For this reason, ceramic waters were chosen as the prefered method of water filtration in our designs.

Ceramic water filters are produced from a mixture of clays and sawdust. The mixtures are then molded into frustum (pot) shapes using molds that are subjected to hydraulic pressure. After drying, the filters are placed in a furnace to sinter and reach a maximum temperature of about 950ºC celsius. At about 500ºC, the sawdust particles burn away, leaving a microporous structure with 500µm sized pores (Annan, 2014). The geometry of this porous network, when doped with chemicals, is very efficient at purifying water at an affordable cost.

Purification Capabilities:

Ceramic water filters have been proven through studies to be very effective in removing microorganisms as well as harmful chemicals within water. For a 50% clay, 50% sawdust composition of a ceramic filter, a 99.97% E. Coli removal rate is possible (Plappally, 2010). Bacterium get trapped in the porous structure of the filter and are not allowed to pass, but the water molecules are small enough to pass through with ease. When treated with chemicals such as hydroxyapatite and alumina oxide, ceramic filters are able to remove chemicals and viruses, respectively.

5.2.2 Methodology

In order to obtain a better understanding of the the ceramic filter technology, numerous filters were manufactured and tested for flow rate characteristics. In addition, filters of various clay/sawdust volume fractions were tested to prove the increase of permeability with an increase of porosity. The final goal was to develop a design that combines several filters together in order to maximize the volume of available water.

Manufacturing Ceramic Filters:

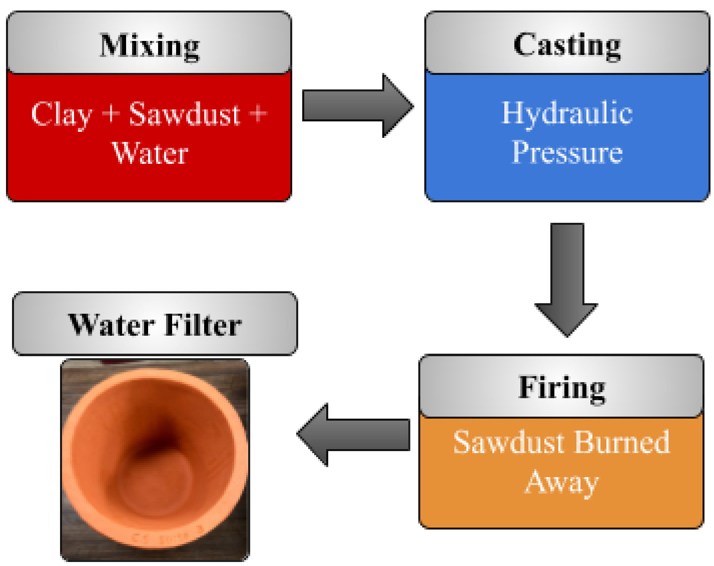


Figure 31: Filter Manufacturing Process

A series of filters were manufactured with a clay/sawdust volume ratio of 50/50. Since only the flow rate was being observed, there was no need for the addition of hydroxyapatite or alumina into the mix. **Figure 31** above shows a simplified version of how the filters were made. Special attention was paid to the surface of the filters to make sure that no cracks began to propagate during the manufacturing process. If cracks formed within the filter, the flow rate analysis would be skewed and filtration would not work as effectively.

Volumetric Flow Rate Analysis:

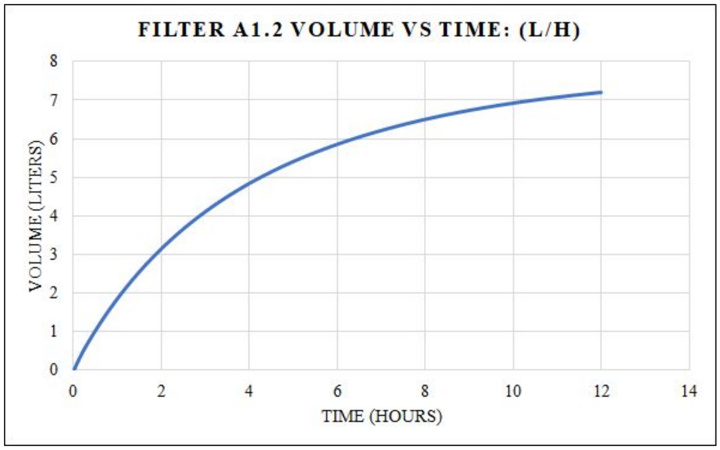
Ceramic filters comprised of different volumetric ratios of clay and sawdust were tested for the flow rate analysis. The goal was to confirm the increase of flow rate with the increase of porosity within the filter. The clay/sawdust ratios tested were of the proportions (45/55), (50/50), and (55,45). As more clay is included in the filter (rather than sawdust), less sawdust is burned away and the lower the porosity and flow rate of the filter. For the study of fluid flow through a porous medium, Darcy's law was used,

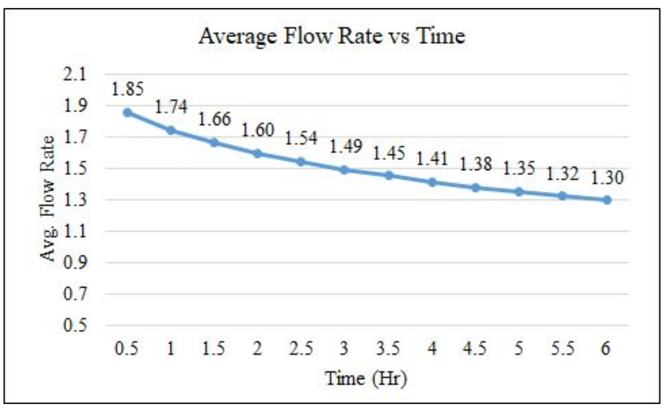
$$Q = \frac{-kA\Delta P}{\mu L}$$

where Q is the total discharge, k is the coefficient of permeability, A is the cross sectional area of flow, ΔP is the change in pressure, μ is the viscosity of the liquid, and L is the length.

Figure 32: Single Filter Flow Rate Test

To establish flow rate characteristics for each volumetric proportion, filters were saturated overnight so that the pores were already filled with water at the start of each experiment. Each filter was filled to the rim with water at the start of the experiment (roughly 8 liters). Next, the filters were allowed to slowly drip the filtered water until they were finished. The dripped water would fall into a bucket that sat on a scale. This scale was hooked up to a computer where data readings were taken every 10 seconds. The data for each test was recorded and formed into graphs and tables like the ones shown below in **Figure 33.** For this experiment, we focused on the first 12 hours of filtration. The decrease in flow rate over time is due to the drop in pressure head in the filter.





Average Flow rates each Hour:	
Time (h)	Avg Flow rate / Hr
0.0 - 0.5	1.8547
0.0 - 1	1.7429
0.0 - 1.5	1.6628
0.0 - 2	1.597925
0.0 - 2.5	1.54286
0.0 - 3	1.494766667
0.0 - 3.5	1.452357143
0.0 - 4	1.4146875
0.0 - 4.5	1.380877778
0.0 - 5	1.35032
0.0 - 5.5	1.322636364
0.0 - 6	1.297391667

Figure 33: Single Filter Flow Rate Test

Multi-Filter Design:

While ceramic filters do a great job in filtering out contaminants thoroughly, they have relatively low flow rates in return. In order to increase the overall flow rate of the filters and total volume of water available for each house, a multi-filter design was created and tested for effectiveness. A brief outline of the filter system is located in **Figure 34** below.

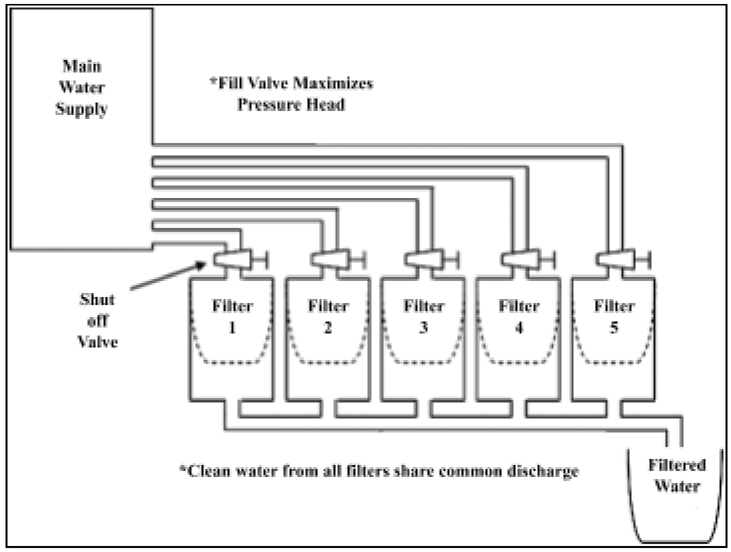


Figure 34: Schematic of Multi-Filter System

The filters are all fed by one main water supply, and the total amount of clean water produced by the group of filters is combined into one common storage tank at the end of the system. One major advantage to the multi-filter system is that it is autonomous, and is only powered through gravity. The system is autonomous because the filters are constantly fed more water from a float valve and the system only relies on gravity to transport the water. By incorporating a float valve into the design, the pressure head of each filter is maintained at a maximum level. This causes the filters to be operating at a maximum flow rate as long as there is enough water to feed them. An image of the manufactured filter system can be seen below in **Figure 35**.

Figure 35: Multi-Filter System

The design of the multi-filter system incorporates a singular source of water located at the center filter of the design. This filter is slightly raised higher than the rest of the filters. As a result, tubing may be used to create a siphoning action that constantly refills the four other filters from the center filter. All of the water is collected underneath the filters through the use of a hydrophobic material such as a shower curtain made out of Polyethylene Vinyl Acetate (PEVA). The catchment surface is positioned at an angle where the water is collected to a common point before dropping down into the bucket to be measured.

5.3 Results & Discussion

5.3.1 Volumetric Flow Rate Results

To compare different volumetric compositions of clay and sawdust, a total of 18 tests were conducted. Two (45/55) C/S filters were tested twice each, Two (55/45) C/S filters were tested twice each, and five (50/50) C/S filters were tested twice each. The average of the two flow rates for each filter was taken and compared in **Figure 36** below.

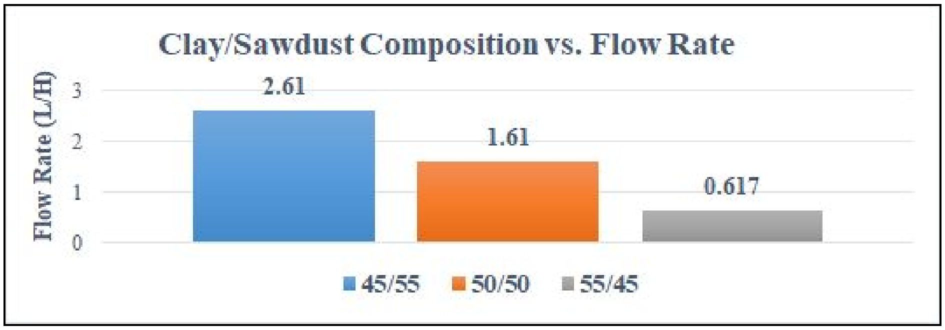


Figure 36: Volumetric Flow Rate Results

As expected, the filter with the highest concentration of sawdust (45/55) C/S had the highest porosity and an average flow rate of 2.61 L/H. The lowest flow rate belonged to the (55/45) C/S volume composition resulted in only 0.62 L/H. It is important to note that all of these values were taken from only the initial s The overall trend from comparing the volume fraction composition to the flow rate was nearly linear.

5.3.2 Multi-Filter Design Results

Average Flow rates each Hour:	
Time (min)	Avg Flow rate / Hr
0.0 - 5	10.9206
0.0 - 10	10.8816
0.0 - 15	10.8746
0.0 - 20	10.8531
0.0 - 25	10.83816
0.0 - 30	10.8245
0.0 - 35	10.81465714
0.0 - 40	10.83816
0.0 - 45	10.8245
0.0 - 50	10.803525
0.0 - 55	10.79293333
0.0 - 60	10.78422

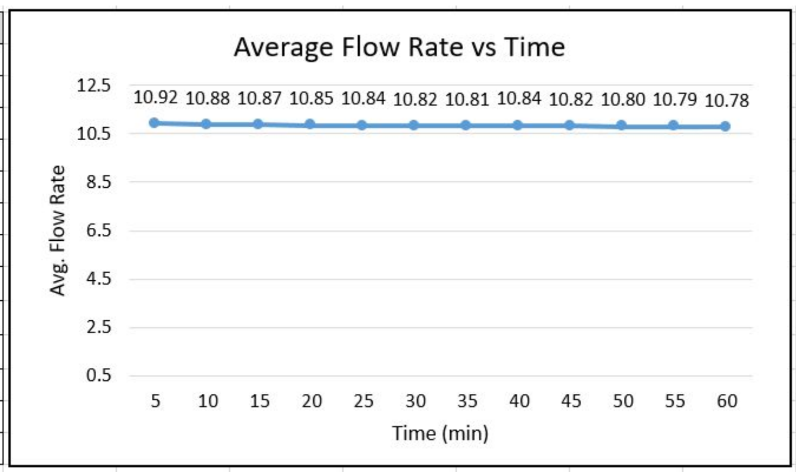


Figure 37: Multi Filter System Flow Rate

As shown in **Figure 37**, after only an hour, the filter was capable of producing over 10 liters of water. In comparison to the previous average of 1.6L/H for a singular filter, the full filter can operate at a much higher potential. With a closer look at the data, one can see that the flow rate drops very slowly. This can be attributed to the water draining out of the four outer filters at a slightly higher rate than the water replacing it. However, a quick adjustment to the height of the center filter can fix this problem. By raising it slightly higher than the outer filters, the difference in height creates a faster siphoning flow into the four outer filters. This resulted in the flow rates reaching steady-state at maximum pressure head.

With the correct set up, this same system could be scaled up to an even larger level, perhaps with 50+ filters. As long as there is a large enough water supply and enough room for the set up, the scalability is very promising. However, for our design, five filters should be suitable to meet the needs of each home.

6.0 Integration & Design

This section will discuss the integration of all technologies researched and tested by the team into a complete home and community design. We will discuss the energy integration (solar panels and wind turbine), the complete building design, the water filtration and collection system, and the financial model.

Figure 38: Integrated Design Model

6.1 Energy Integration

Solar Panel Integration into House:

Nigeria's latitude is approximately 8.867 degrees, which differs from Massachusetts latitude. This means that our solar panel angle should be optimized for Nigerian latitude. This allows us to maximize the current output of the solar panel because when we maximize the current, we thus maximize the power output. When we maximize the power output of the solar panel, we can come extremely close to our joint testing goal of 24V voltage output and thus storage capacity.

From the latitude of Nigeria, we can simply multiply by 0.87 to achieve the optimal solar panel angle tilt. This give us an angle of approximately 7.71 degrees. From our structural analysis, we determined that the minimum angle our roof has to achieve is 5 degrees in order to account for water drainage. With this in mind, our optimal solar panel angle tilt exceeds this minimum and thus is safe to be integrated into the house at maximum efficiency.

When we consider the results we achieved from solar panel testing, we can clearly see that our solar panel will not only provide enough power to a typical Nigerian family, it will also properly integrate into our housing design as to not interfere with basic structural necessities like the roof angle. Additionally, since one side of our roof is 60.8 m^2, we can assume that we can fit more than one solar panel based on the size of the panels we used for testing.

6.2 Integrated Building Design

Architectural Layout:

Our building design layout was modelled from previous layout found in another study (Okwo, 2005). The building is intended from low to middle income families in Nigeria, but can be replicated or modified in most countries. The rectangular design of the single story residential building is straightforward and uncomplex for the purpose of reducing construction and building cost, as well as design uniformity. The building materials which were chosen can be produced locally in Nigeria but are also found in most developing countries. For our purpose, we used the

International Building Code 2018 and Nigeria Building Code 2006 as references. Standards from ASCE 7 and methods from "Design of Wood Structures" by Donald Breyer were also used.

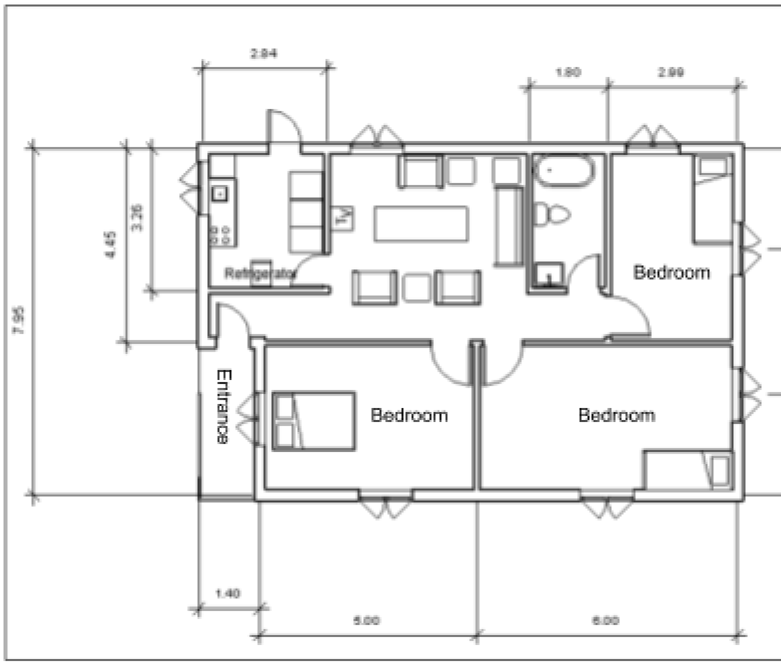


Figure 39: First Floor Plan

The floor plan consist of three bedroom, one bathroom, one kitchen and one living room. The building footprint is 26' x 40.68'(7.95m x 12.4m), which is a total space of 1061.1 sq-ft (98.58 m^2). The house is 8ft tall and has a sloped roof of 4.11 in/ft. The roof frame plan (Fig 40) consist of two different joist (P1,P2), three different girder (G1,G2,G3), and three different columns (C1,C2,C3)

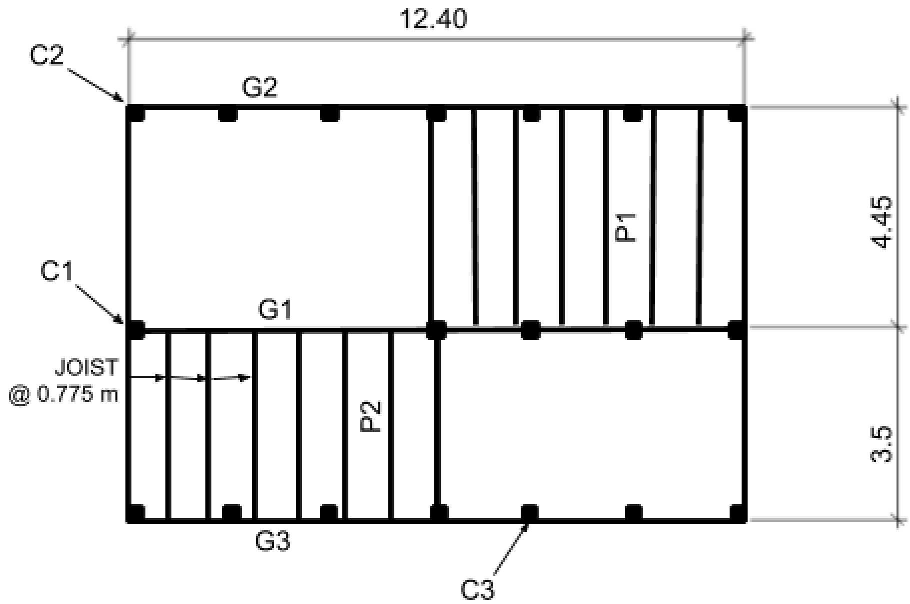


Figure 40: Roof Frame Plan

Structural Wood Design

Wood structural are common materials used for single family residences (Breyer, 1988). Our building would be a wood-frame construction. Our analysis will focus on the roof and column design. Only dead and live loads were considered as Nigeria does not require seismic (earthquake loads) and the wind loads are negligible for a one-story residential home . The method used to determine the loads and structural member is Allowable Stress Design (ASD). Table 2 shows the load combination for the roof design.

Dead Load (psf)		Live Load (psf)	
Roofing (Galvanized Steel)	2.5	Roof Live Load	20
Framing	2.0		
Suspended Ceiling	2.5		

Reroofing	1		
Insulation	0.5		
Total Dead Load	8.5	Total Live Load	20
Load Combination (D+L)		8.5 + 20 = 28.5 ~ 29 psf	

Table 3: Structure Wood Design Characteristics

Due to the lack of standardized wood materials in Nigeria, wood and their properties were selected from National Design Specification Supplement. White Oak and Red Maples were chosen as they are common in Massachusetts. With ASD, the reliability of the design is based on maximum bending moment, shear, deflection, and bearing. The ASD equations and calculation can be found in Appendix C. Table 3 shows the structural size of each member.

Members	Selected Graded Dimension Lumber Size (* = Posts and Timbers)
J1	3” x 10”
J2	3” x 10”
G1	12” x 14” *
G2	4” x 16”
G3	4” x 16”
C1	4” x 6”
C2	4” x 6”
C3	4” x 6”

Table 4: Graded Dimension Lumber Size

The floor design will be disregarded as there no structural support for it and it can be built for the earth (ground) to support the load.

6.3 Integrated Supply of Clean Water

To integrate a supply of clean water into our housing design, each house would be outfitted with a rainwater harvesting system as well as multi-filter system that is capable of producing up to 10 L/H of clean water. The catchment surface of the roof provides ample surface area for a volume of water that supports a full family. Since the design of the water system relies on natural forces such as rainfall and gravity, the system can be produced at an affordable cost, and can be maintained with sustainable methods.

6.4 Financial Model

In looking at the entirety of the house and all of the sustainable solutions we offer, we see this house design as being very practical for our target demographic. As previously mentioned, we originally set out to design this house with the lowest income bracket of Nigerian families in mind. We wanted to increase their living standards by providing them with electricity, water, and a safe shelter in a sustainable and affordable way. In this sense, the integration of our technicolgies has seamlessly provided a solution to our goal.

6.4.1 Funding & Investments

In order for our design to truly be a global approach to affordable housing, our model shouldn't have to rely heavily on government aid to succeed. By relying on outside funding from investors and philanthropic organizations, the model can work more on an independent level. This could prove helpful in regions or countries where the government may be corrupt or not stable.

An overview of cash flow within the financial model can be seen in the **Figure 41** below. In summation, initial loans of very low interest rates (1-2%) are given to mortgage banks that are local to the developing region. Next, these local mortgage banks offer slightly higher interest rates (3-5%) to contractors and residents planning on living in the community. The entire cost of the community is eventually split throughout the 200 people living in the area, and these customers end up paying back the mortgage banks with interest. By the end of the payment plans, everyone is happy because the banks are making some profits over the course of several years, contractors have work they can accomplish and be compensated for, and the residents have a home to call theirs with sustainable technologies for years to come.

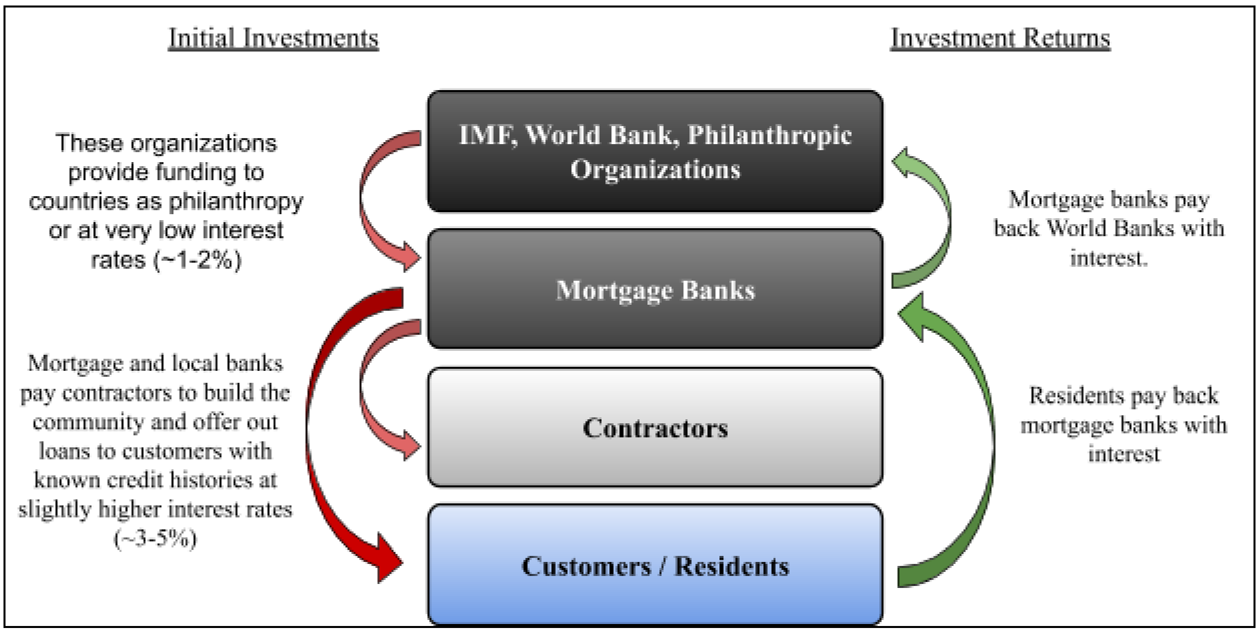


Figure 41: Overview of Cash Flow in the Model

6.4.2 An Adaptable Model

Perhaps the most notable aspect of this project, apart from it's promising technological and financial implications, is its adaptability. Specifically, the financial model and validated technologies are dynamic. This means that they can be either enhanced or minimized in order to meet the needs of different families in different contexts. These different contexts include, but are not limited to:

- Different local building materials, yearly rainfall averages, sun coverage and wind speeds
- Evolving and differing energy needs

- Varying income levels

For example, simple financial calculations and research into energy and housing needs for varying income levels will result in a tiered system, as shown below:

Design	Income	Energy System Needs	House Specifications
Lowest Income Design	Income: $ 30-60 / month	Energy: 6v-12v System	House: 1-3 bedrooms
Middle Income Design	Income: $150-400 / month	Energy: 12v-24v System	House: 3 bedrooms
Upper Income Design	Income: $3,000 + / month	Energy: Tesla Battery System	House: 3+ bedrooms

Table 5: Multi-Tier Income System

As displayed in the figure above, as the income increases, so do the energy system needs and house specifications. At this point, simple variable changes in our calculations are all that is needed to adjust the amount of solar panels, turbines and house layout to match the income level. This is just one example of the adaptability of the house. The same principles apply to the amount of water filters based on changing rainfall statistics per area and building materials based on local accessibility and climate.

6.4.3 Cost Breakdown of Home

Our goal is to create communities that will foster better environments and opportunities for families to grow and children to be raised. This community based approach will also aid in keeping the individual cost per home down because the cost for communal needs can be broken down and divided per home. For this we referenced *An Alternative Approach to Affordable Housing: Homes of Foam by A. Okwo and W.O. Soboyejo* who had similar interests in creating new technologically inclusive homes and communities for the low and middle income.

To create an affordable system, the main objective has to be to minimize the cost of material, labor, infrastructure, and interest payments, as these are significant areas of cost. The following equation is from the paper showing the above concept mathematically.

$$\min_{\vec{n},\ \vec{x},\ L,\ y} \sum_t \sum_i c_i n_t^{(i)} + \sum_t w_t L_t + \sum_t P_t + K + I - \sum_t y_{t-1}(1 + r)$$

Figure 42: Cost Model

Where the first summation (∑∑) is the total cost of building materials multiplied by the number of materials needed. The second summation is the total cost of labor (rate of each laborer multiplied by number of laborers during period). The next summation takes into account the sum of all debt payments (principal plus interest), fixed and constant capital/equipment costs, and fixed infrastructure costs; then finally everything is subtracted by the sum of the money invested.

Using this concept we estimated the cost of our home to be around $25,000. After completing the structural analysis of the home, a complete list of building materials was determined and estimates for pricing was found to be $16,876 per home. This cost could be significantly lowered by partnering with organizations and lumber retailers for bulk orders as well as incentives from investors and banks.

Next, land costs were determined from Nigerian property sale websites and estimated to be $649 per home. The total land needed was estimated based on a 200 home community and using a residential design guide by the United Kingdom, stating that the minimum distance between homes should be 72 feet (Supplementary Planning Documents and Guidance, 2018). From this each home would have a property size of 6,278 ft^2 (86’x73’) and in total would need around 29 acres of land. In order to have enough recreation space, the land was doubled to nearly 58 acres. Using these Nigerian land purchasing websites, this amount of land only resulted in nearly $130,000, which distributed over 200 homes is $649. There are additional fees associated with purchasing land however. These include a survey plan (roughly 300,000 Naira), legal fee (5% of land cost), and agency fee (5% of land cost) (Buying Land in Nigeria, 2018). Per home, these extra costs come out to $70.

Infrastructure was a major priority of developing a community. Our focus was on new types of natural fiber reinforced asphalt and concrete for building the roads and sidewalks of our new community. We conducted research into the standards for roads and sidewalks and how thick the asphalt is typically in these areas. We found that roads are usually 20 feet wide (10 ft for each lane) (Ink, 2015) and sidewalks 7.7 feet including the curb (Federal Highway Administration University Course on Bicycle and Pedestrian Transportation, 2006), and that the asphalt thickness is typically 11 inches (Chapter 4 Thickness Design, n.d.). And since each home had to be 72 feet away from each other we needed nearly 1.2 miles of road. However, natural fiber reinforced asphalt is still being researched and tested and is not commercially available yet. Because of this for cost analysis we used the bricks created for the home for the roads. Using the information found for asphalt, we calculated the amount of brick necessary and estimated the cost of labor (U.S. $400 which is nearly 150,00 Nigerian Naira) and found the total to be U.S. $2151 which is nearly $11 per home.

Recreation includes land for families to use as well as a soccer field, because soccer is a major sport in Nigeria. The organization *It Starts with Soccer* has been building communities and soccer fields with the goal of "helping underserved children break out of the cycle of poverty so they can lead successful and prosperous lives." Their average cost estimate of each soccer field is $3000 ($15 each home) which involves clearing the field and installation of goals, nets, and flags (Soccer Field Construction, 2018). This cost was taken into account along with the cost of recreation from the *An Alternative Approach to Affordable Housing: Homes of Foam by A. Okwo and W.O. Soboyejo* who's recreation cost is $378 per home. Adding this to the cost of the additional soccer field wouldn't be much for the homeowner. An additional cost from this paper was the cost of sanitation, which was estimated to be $1,134 per home.

Next we estimated the price of lighting and appliances. Since we are designing for an electrical need of the home, we want to make sure the appliances in the home meet the energy requirements. The cost of lighting is roughly $100, TV is $400, fans(three) are $120, and refrigerator is $600. Total the lighting and appliances should be $1020 for each home, which is a significant amount that could be lowered with partnering with retailers. The battery system to power this is also expected to be $1020 as the house needs nearly 3 kWh of electricity per day. However the electrical need and cost of appliances and battery system can all be reduced depending on the income level of the individual and family. The electrical need of the home was also cross-checked with *Estimating Residential Electricity Consumption in Nigeria to Support Energy Transitions by Kayode Olaniyan, Benjamin McLellan, Seiichi Ogata, and Tetsuo Tezuka (*Olaniyan, Mclellan, Ogata, Tezuka, 2018*)* for accuracy.

Final costs of the home include the water filtration system, the solar panels, the wind turbine, and extra safety measures. The water filtration system is $700, this includes the filters, the housing, and the components to attach from the home to the system. The solar panel cost can vary depending on the need of the home. The large 65 Watt solar panel is $280 (BP SOLAR 65Watt, 2019) and the price of the smaller 5 Watt panel is $23 (SolaLand, 2019). The price of the wind turbine as created by the group at UVM is $2,562 because of the aluminum housing and tubing to get it 10 feet in the air, which was $1,589 of the total cost. This cost could also be reduced either by choosing a different material for the construction or by again buying the material in bulk from an organization with incentives from the banks. The last component of the cost per home is the safety. This includes a first aid kit, a fire extinguisher, and a backup generator in case all else fails.

In total the house should cost roughly $25,000 for a middle class family with all the components listed above, which per month would still be 30% of the income of an individual making $8 a day.

7.0 Recommendations

7.1 Energy Recommendations

Below is a breakdown of the energy consumption and corresponding energy solution that can provide for that consumption:

Energy Source:	**Power Applications (per day)**
Wind Turbine Wattage: 5 W	Lights (4 hrs), Cell Phone Charging (4 hrs)
Solar Panels Size: 2.267 m^2 Wattage: 5 - 60W	Lights (4 hrs), Cell Phone Charging (4 hrs), Fan (5 hrs), Refrigerator (24 hrs)
Solar Panels **+ Wind Turbine** Wattage: 10 - 65 W	Lights (4+ hrs) Cell Phone Charging (4+ hrs), Fan (5+ hrs), TV (4+ hrs), Refrigerator (24 hrs)

Table 6: Energy Breakdown by Energy Source and Application

To fulfill the Solar Panel + Wind Turbine power application needs, we recommend utilizing one wind turbine and four 25W panels. This will meet the power needs of low - income families. Two panels will be on both sides of the roof, with enough room to add more solar panels if desired. The four panels will be able to provide enough energy for 30 LED lights, three fans, one refrigerator and two cell phones (charging outlets).

7.2 Building Recommendations

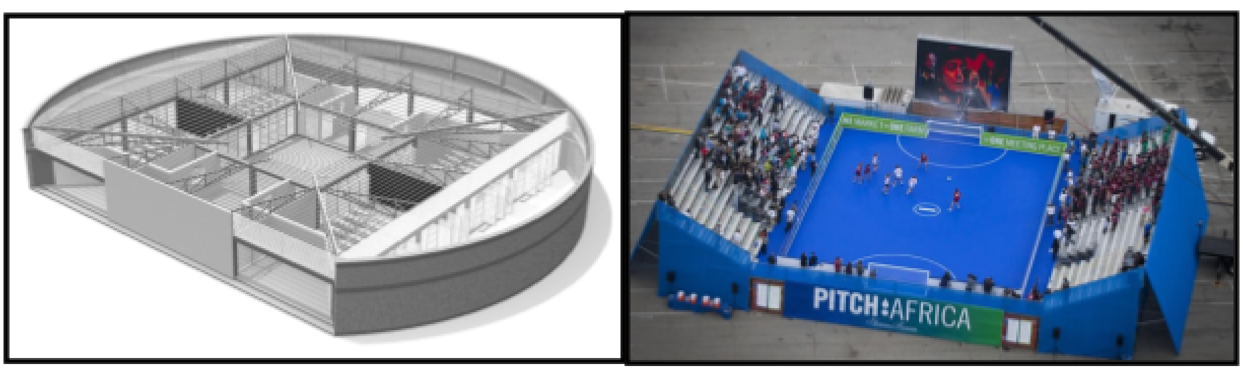
To decrease the building material cost even further, bamboo should be considered. Bamboo has been used as a building material commonly in East Asia, and it is also known for its ability to grow all round the world in different climates. Bamboo can be used as the roofing tile or building columns.

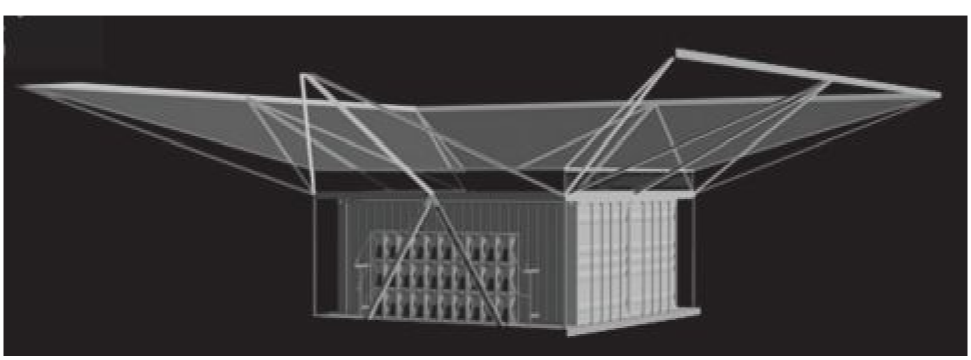
The clay/cement bricks are intended to be used for the outer walls of the house while the sandwich panels will be used for the inner walls. Since none of the weight of the house is carried by the outer or inner walls, these materials are viable options for the walls. More work needs to be done to find the fracture toughness and the resistance-curve behaviour of the bricks. Due to lack of funds and accessing to high precision tools, the measurements of samples were not accurate which may lead to slightly inaccurate representation of materials properties. Work done by Kabiru et al provides information about other affordable building material alternatives that can be alternatives that also be utilized in the housing design.

7.3 Clean Water Recommendations

In order to meet the needs of a community sized demand for water, a community filter bank may be incorporated into the 200 home community model. Models such as the ones developed below from Atopia Research have already been implemented counties and have been proven to work on a large scale. The smallest design of the three makes use of not only rainwater harvesting, but the same ceramic water filters that were used in this project. It is made up of two shipping crates and when the system is fully filled up, it is capable of holding 60,000L of water at a time. If just one of these designs were used in the development of a community, there would be no shortage of clean water available to consume.

Figure 43: Community Filter Bank Designs (Atopia Research)





8.0 Conclusion

Overall, we conclude that our house design is viable within a Nigerian context. This is proven and demonstrated by our validated technologies and comprehensive financial model. It is important to understand that our validated technologies and financial model are intertwined and cannot exist without each other. Our technologies provide stable water and energy supply, and a suitable shelter. Our financial model makes the implementation of those technologies a reality by providing an attainable method for low-income families to pay for the house over time. Additionally, our house design and financial model is adaptable to worldwide markets. Parameters like the wall thickness, wall material, number of solar panels, number of clay filters and financing options are all that need to be adjusted when transferring this design to other cultural and environmental contexts.

This project was done over the course of 8 months. Naturally, there was material we did not have time to include in our research. Namely, a more in-depth analysis on thermoelectric technology was a topic we did not have the time to research and test. Future projects and work in this area could involve developing a proprietary thermoelectric that generates enough electricity to compete with the viability of the wind turbine. As mentioned before, our model is adaptable to worldwide markets. As such, future projects should also delve deeper into this area and analyze the logistics of this model's adaptability and rate it's viability across a multitude of countries, cultures and contexts. Future projects should also take a closer look at implementing our model across different income levels. For this project, we mainly focused on low-income families. However, this model can be adapted to fit the needs of middle and high-income families, and future projects could tailor the model to address these needs.

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Appendix A: Design Statement

The project was a combination of mechanical and civil engineering. The project includes the integration of sustainable energy, alternative building material, and clay water filtration system into an affordable and adequate residential home. Wind energy and Solar energy were chosen as a source of energy by using PV panels and wind turbine. There were substantial testing (realistic and simulated) on the performance at different conditions to determine the reliability. A clay filtration system was created to increase the filtration rate from 1.6L/hr for one clay filter to 10L/hr for 5 clay filters. Alternative building materials were researched such as clay and cement mixture to decrease production cost.

In order to meet the CEE capstone requirements for the Major Qualify Project at Worcester Polytechnic Institute, a design and structural plan. The design problem is to do the structural analysis of our building. Our building is a one floor residential home includes three bedrooms, a kitchen, a bathroom, and a living room. The IBC Code 2018 and ASCE 7 standards were used as references. The site location is in Aja, Lagos, the U.S.A. Since the land is vast, there is not enough information about the land. The house design is incorporated into a 200 home community plan developed for families of different incomes.

Through these deliverables, a solution for affordable and sustainable housing was produced and shown to be practical. This project encourages the onward push to a more green and environmentally friendly future

Appendix B: License Statement

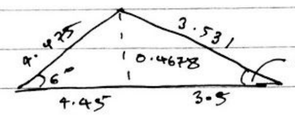
There are three phases to obtain professional licensure. The Fundamentals of Engineering (FE) examination must be passed to complete the first step. The FE exam (Civil specific) covers variety of engineering disciplines: mathematics, probability and statistics, computational tools, ethics and professional practice, engineering economics, statics, dynamics, mechanics of materials, materials, fluid mechanics, hydraulics and hydrologic systems, structural design, geotechnical engineering, transportation engineering, environmental engineering, construction, and surveying. The status of an Engineering-in-Training (EIT) will be obtained after passing.

After four years, an individual can take the Principles and Practice of Engineering (PE) Examination. This exam is field specific, which includes: structural, construction, transportation, geotechnical, and water resources and environmental. The PE license is beneficial for society as it is a benchmark for professional and grantees that engineers have adequate background and education to safely and reliably complete an engineering task. It also helps grows and standardize the industry.

Appendix C: Structural Analysis

Structural Analysis

Roof



slope = 4.11 in/ft

Dead Load

→ Roofing (Deck Metal (Galvinzed steel, 20 gauge) 2.5 psf

→ Framming 2.0 psf (2X12, 24 in O.C.)

→ Suspended ceiling (Wood furring Suspension) 2.5 psf

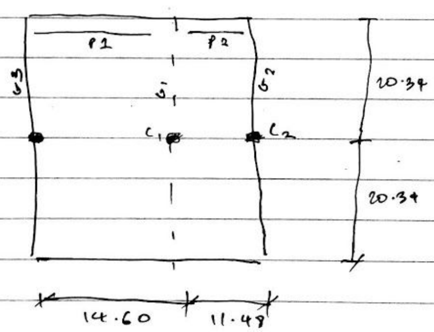
→ Reroofing 1 psf

→ Insulation 0.5 psf

TOT = 8.5 psf → 9 psf

Live Load

→ Roof 20 psf (ASCE 7)



P1

Tributary Width = 2.5425 ft

Span = 14.6 ft

A_T = 37.1205 ft^2

P2

Tributary Width = 2.5425 ft

Span = 11.48 ft

A_T = 29.1879 ft^2

G1

Tributary Width = 13.04 ft

Span = 20.34 ft

A_T = 265.23 ft^2

G2

Tributary Width = 5.74 ft

Span = 20.34 ft

A_T = 116.75 ft^2

G3

Tributary Width = 7.3 ft Span = 20.34 ft A_T = 148.482 ft^2

C1

Tributary Width = 20.34 ft

Tributary Length = 13.04 ft

A_T = 265.23 ft²

$K_{LL} \times A_T$ = 4 × 265.23 ft² = 1060.92

Roof Loads

G1

L_0 = 20 psf

R_1 = 1.2 − 0.001 (265.23) = 0.935

F = 1.2 − 0.05 (4.11) = 0.995

$L_{r'}$ = 20 × 0.935 × 0.995 = 18.61

ω = [9 + 18.61] [13.04] = 360.034 lb/ft

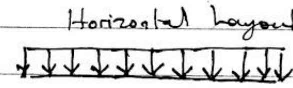
C1

A_r = 265.23 ft²

L_r = 18.61

P = [9 + 18.61] [265.23] = 7323 lb

Horizontal Layout



P1

A_T = 37.1205 ft² < 200 ft²

L_r = 20 psf

ω = (9 + 20) (2.5425) = 73.73 lb/ft

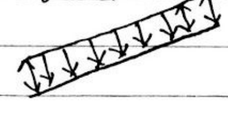
P2

A_T = 29.1879 ft² < 200 ft²

L_r = 20 psf

ω = (9 + 20) (2.5425) = 73.73 lb/ft

slope Layout



$\omega_{TL} = \omega_D + \omega_{Lr}\left(\frac{L_2}{L_1}\right)$

P1

$\omega_{TL} = 9(2.5425) + 20(2.5425)\left(\frac{14.6}{14.682}\right) = 73.44$ lb/ft

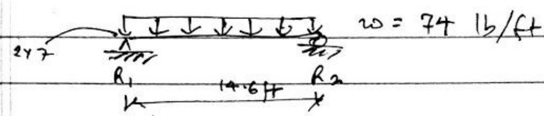
P_2

$\omega_{T_2} = 9(2.5425) + 20(2.5425)\left(\frac{11.58}{11.48}\right) = 73.294$ lb/ft

Beam Deflection Limits

$$\Delta = \frac{5wL^4}{384EI} \le \frac{L}{360} \quad [L] \qquad \frac{L}{240} \quad [D+L]$$

$P1$



$$R_1 = R_2 = \frac{wL}{2} = \frac{74 \times 14.6}{2} = 540 \text{ lb}$$

$$M_{max} = \frac{wL^2}{8} = \frac{74 \times 14.6^2}{8} = 1971.73 \text{ lb-ft}$$

$$\Delta = \frac{5\left(\frac{74}{12}\right)(14.6 \times 12)^4}{384(1.3 \times 10^6)(34.33)} = 1.675 \text{ in}$$

$$I_x = \frac{1\tfrac{1}{2} \times [6\tfrac{1}{2}]^3}{12} = 34.33$$

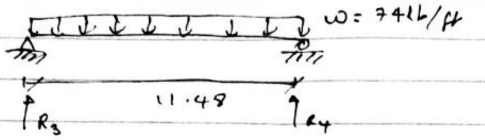
$$\frac{L}{240} = \frac{146 \times 12}{240} = 0.73 \text{ in} \quad \therefore \text{ NOT GOOD}$$

Try 3x10

$$I = \frac{2\tfrac{1}{2} \times [9\tfrac{1}{2}]^3}{12} = 178.61$$

$$\Delta = 0.3258 \quad \therefore \text{ GOOD!!}$$

r2



$R_3 = R_4 = \frac{wL}{2} = \frac{74 \times 11.48}{2} = 424.76$ lb

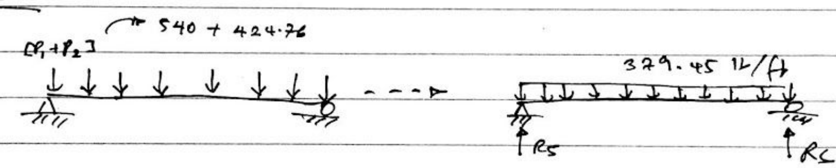
$M_{max} = \frac{wL^2}{8} = \frac{74 \times [11.48]^2}{8} = 1219.06$ lb-ft

Try 3x10

$I_x = 178.61$

$\Delta = \frac{5\left(\frac{74}{12}\right)(11.48 \times 12)^4}{384\,(1.3 \times 10^6)\,(178.61)} = 0.125$ in

G1



$R_5 = R_6 = \frac{wL}{2} = \frac{379.45 \times 20.39}{2} = 3859.04$ lb

$M_{max} = \frac{wL^2}{12} = \frac{379.45 \times [20.34]^2}{8} = 19623.05$ lbft

Try 4x14

$I_x = \frac{3\frac{1}{2} \times [13\frac{1}{2}]^3}{12} = 717.6$

$\frac{L}{240} = \frac{20.34 \times 12}{240} = 1.017$ in

$\Delta = \frac{5wL^4}{384\,EI} = \frac{5 \times \left(\frac{379.45}{12}\right)(20.34 \times 12)^4}{384\,(1.3 \times 10^6)\,(717.6} = 1.54$ in

∴ NOT GOOD

Try 4x16

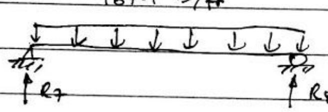
$$I_x = \frac{3\frac{1}{2} \times (15\frac{3}{4})^3}{12} = 1139.53$$

$$\Delta = \frac{5wL^4}{384EI} = \frac{5 \times \left(\frac{379.45}{12}\right)(20.34 \times 12)^4}{384 \times (1.3 \times 10^6)(1139.53)}$$

$$= 0.986 \text{ in}$$

1.017 in > 0.986 in ∴ GOOD

G2



$$R_7 = R_8 = \frac{wL}{2} = 1699.41 \text{ lb}$$

$$M_{max} = \frac{wL^2}{8} = \frac{167.1 \times 20.34^2}{8} = 8641.48 \text{ lb-ft}$$

$$\frac{L}{240} = 1.017 \text{ in}$$

Try 4x10

$$\Delta = \frac{5 \times \left(\frac{167.1}{12}\right)(20.34 \times 12)^4}{384 (1.3 \times 10^6)(250.1)} = 1.979 \text{ in}$$

∴ NOT GOOD

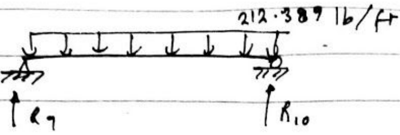
Try 4x14

$$I_x = \frac{3\frac{1}{2} \times [13\frac{1}{2}]^3}{12} = 717.61$$

$$\Delta = \frac{5\left(\frac{167.1}{12}\right)(20.34 \times 12)^4}{384 \times (1.3 \times 10^6) \times 717.61} = 0.670 \text{ in}$$

1.017 in > 0.670 in ∴ GOOD

G3



$R_9 = R_{10} = \frac{wL}{2} = 2160$ lb

$\frac{L}{240} = 1.017$

$$\Delta = \frac{5 \times \left(\frac{212.389}{12}\right) \times (20.34 \times 12)^4}{384 \times (1.3 \times 10^6) \times 717.61} = 0.877 \text{ in}$$

1.017 in > 0.877 in ∴ GOOD

P1 =	3x10
P2 =	3x10
G1 =	4x16
G2 =	4x14
G3 =	4x14

(8)

G 2

4x14

M_{max} = 8641.48 lbft or 103697.76 lbin

F'b = 983.25 psi

Req'd S = $\frac{103697.76}{983.25}$ = 105.46 psi

$S_{for\ 4x14}$ = 102.41 < 105.46 ∴ NOT GOOD

Try 4x16

S = 135.66 ∴ GOOD!!

f'b = $\frac{103697.76}{135.66}$ = 764.394

C_F = 0.97

F'b = 950x09 x1.15 x0.97 = 953.75

764.394 < 953.25 GOOD

G 3

4x16

$M_{max} = \frac{wL^2}{8}$ = 10983.58 lbft or 131802.96 lbft

Req'd S = $\frac{131802.96}{983.25}$ = 134.04

135.66 > 134.04 GOOD

f'_b = $\frac{131802.96}{135.66}$ = 971.568

F'b = 950 x0.9 x1.15 = 983.25

971.568 < 983.25 ∴ GOOD

G 2

4x14

M_{max} = 8641.48 lbft or 103697.76 lbin

F'_b = 983.25 psi

Req'd S = $\frac{103697.76}{983.25}$ = 105.46 psi

S for 4x14 = 102.41 < 105.46 ∴ NOT GOOD

Try 4x16

S = 135.66 ∴ GOOD!!

f'_b = $\frac{103697.76}{135.66}$ = 764.394

C_F = 0.97

F'_b = 950x09 x1.15 x0.97 = 953.75

764.394 < 953.25 GOOD

G 3

4x16

M_{max} = $\frac{wL^2}{8}$ = 10983.58 lbft or 131802.96 lbft

Req'd S = $\frac{131802.96}{983.25}$ = 134.04

135.66 > 134.04 GOOD

f'_b = $\frac{131802.96}{135.66}$ = 971.568

F'_b = 950 x0.9 x1.15 = 983.25

971.568 < 983.25 ∴ GOOD

P1 = 3 × 10

P2 = 3 × 10

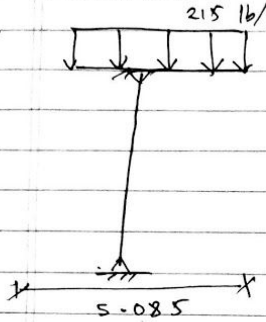
G1 = 12 × 14

G2 = 4 × 16

G3 = 4 × 16

Columns

C2



P = 1093.275 lb

Try ~~2x12~~ 4 X 6

F_c for Red Maple = 925 psi

$C_D = 1$

$C_m = 0.8$

$C_r = 1.0$

$C_F = 1$

$C_p = 1$

$C_i = 1$

$E_{min} = 330{,}000$ psi

A = ~~1½ x 11½ = 17.25~~ 3½ x 5½ = 19.25

$\frac{l_e}{d} = \frac{8 \times 12}{3.5} = 27.43$

$E'_{min} = 330{,}000 \times 0.8 \times (1) \times (1) \times (1) = 264000$ psi

$F_{cE} = \frac{0.822\,(264000)}{(27.43)^2} = 288.419$ psi

$F_c^* = 925 \times 0.9 \times 0.8 \times 1 \times 1 \times 1 = 666$ psi

$\frac{F_{cE}}{F_c^*} = \frac{288.49}{666} = 0.433$

$\frac{1 + F_{cE}/F_c^*}{2c} = \frac{1 + 0.433}{2\,(0.8)} = 0.895$

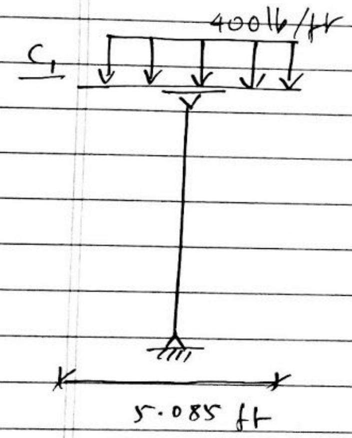
$C_p = 0.895 - \sqrt{0.895^2 - \frac{0.433}{0.8}} = 0.385$

$F_c' = 925(0.9)(0.8)(0.385) = 256.41$

$P = F_c' A = \sout{256.41}\ 0.25641 \times 19.25 = 4.936\ K$

$1.093K < 4.936\ K$

$\therefore$ GOOD



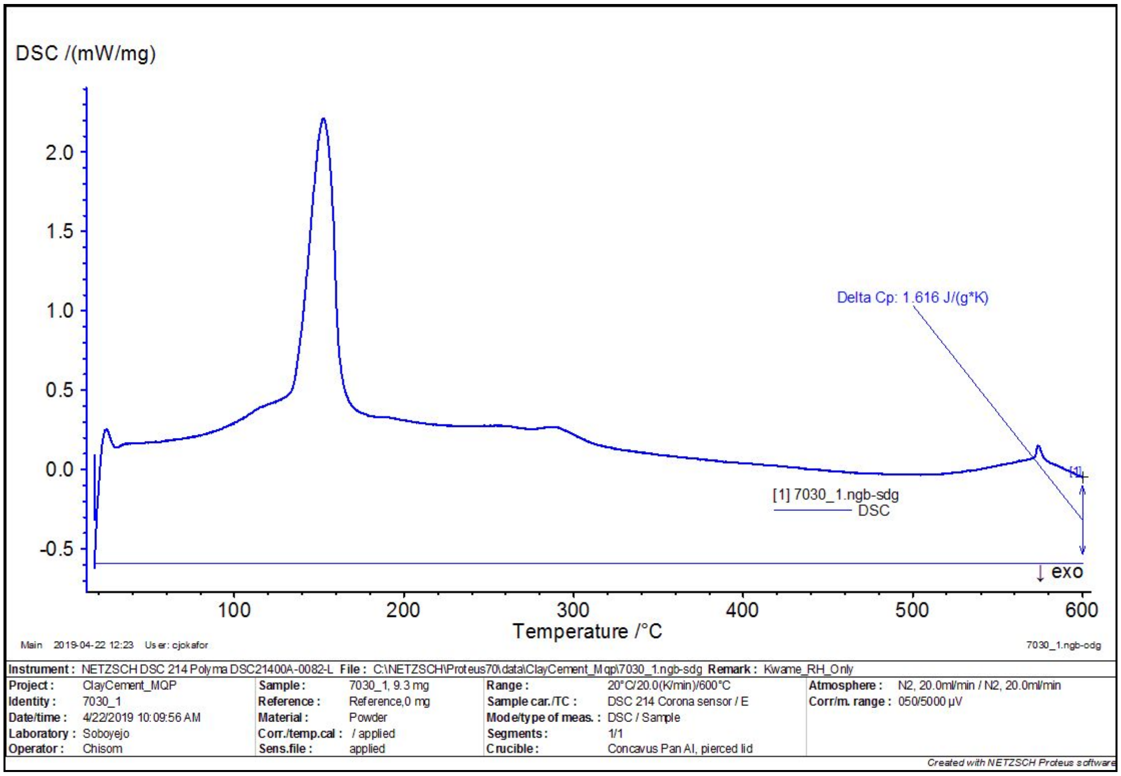
$P = 400 \times 5.085 = 2034$ lb

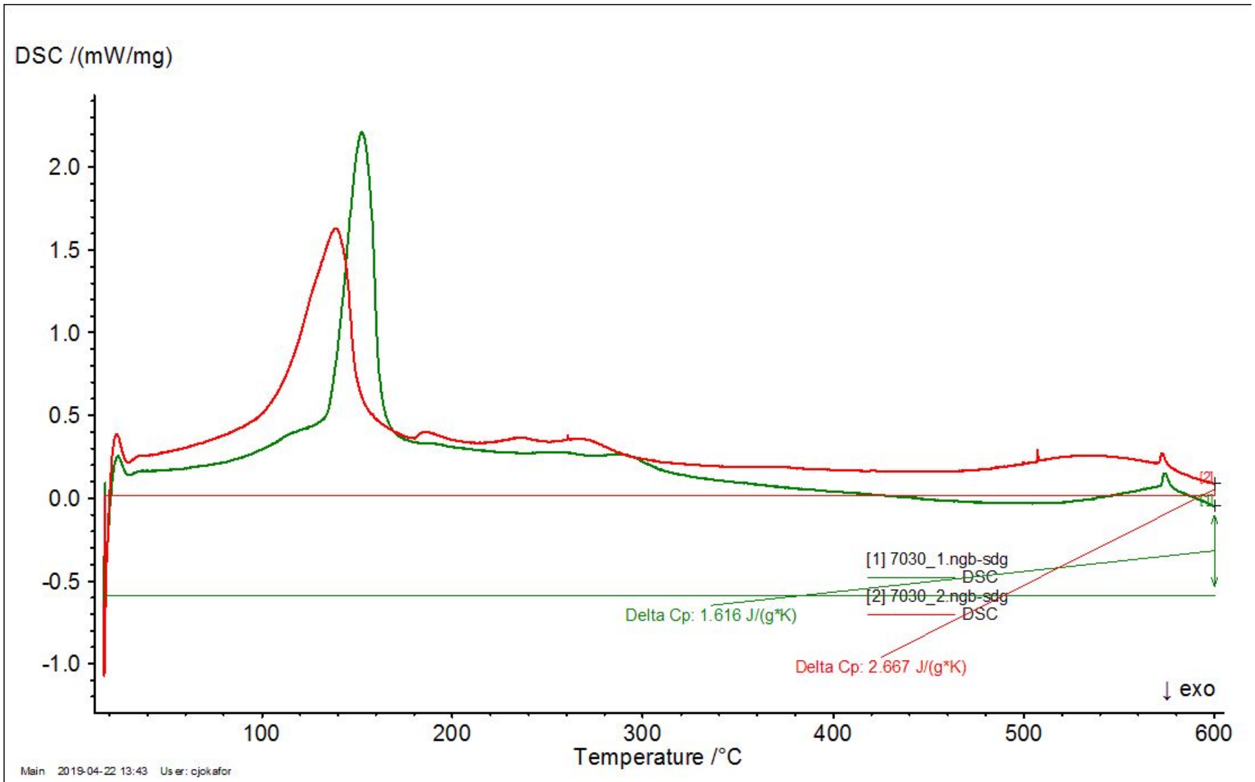
Therefore

$2.034\ K < 4.936K$

GOOD!!

Appendix D: DSC Data





[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[1] DSC 214 Polyma	7030_1.ngb-sdg	2019-04-22	7030_1	7030_1	9.3	1/1	20°C/20.0(K/min)/600°C	N2, 20.0ml/min / N2, 20.0ml/min	050
[2] DSC 214 Polyma	7030_2.ngb-sdg	2019-04-22	7030_2	7030_2	11.4	1/1	20°C/20.0(K/min)/600°C	N2, 20.0ml/min / N2, 20.0ml/min	050

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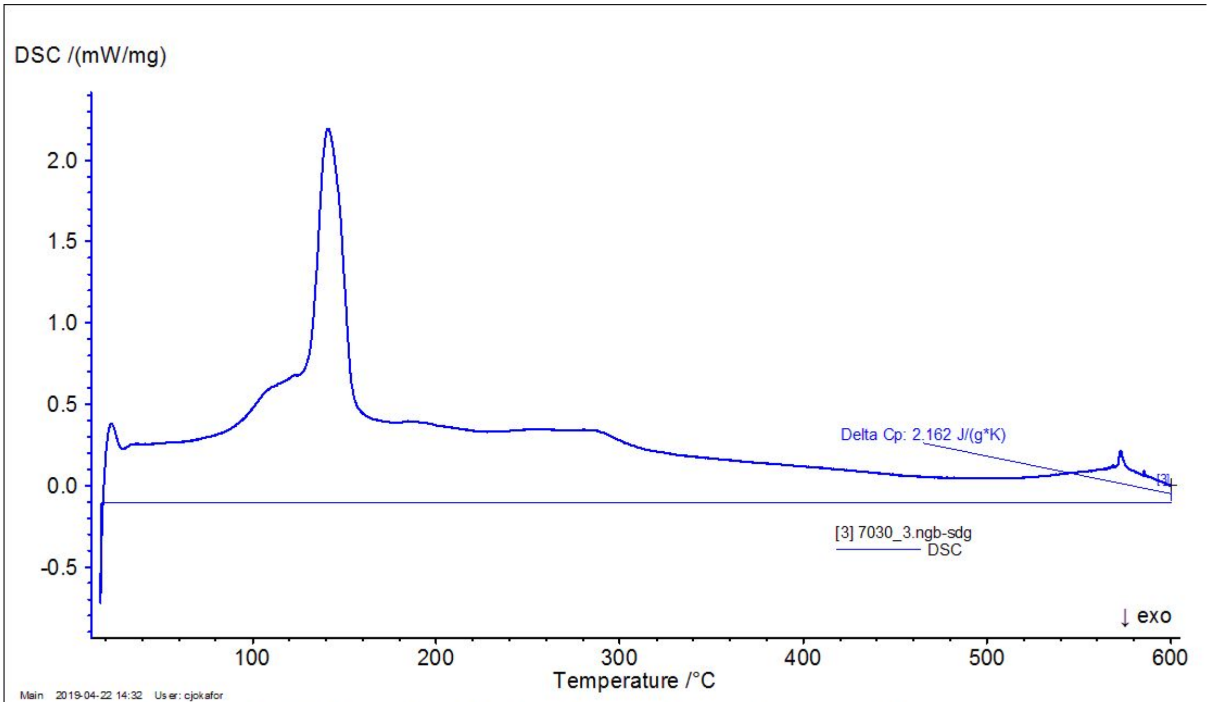

Instrument : NETZSCH DSC 214 Polyma DSC21400A-0082-L **File :** C:\NETZSCH\Proteus70\data\ClayCement_Mqp\7030_3.ngb-sdg **Remark :** Kwame_RH_Only

Project :	ClayCement_MQP	**Sample :**	7030_3, 11.4 mg	**Range :**	20°C/20.0(K/min)/600°C	**Atmosphere :**	N2, 20.0ml/min / N2, 20.0ml/min
Identity :	7030_3	**Reference :**	Reference,0 mg	**Sample car./TC :**	DSC 214 Corona sensor / E	**Corr/m. range :**	050/5000 µV
Date/time :	4/22/2019 1:55:07 PM	**Material :**	Powder	**Mode/type of meas. :**	DSC / Sample		
Laboratory :	Soboyejo	**Corr./temp.cal :**	/ applied	**Segments :**	1/1		
Operator :	Chisom	**Sens.file :**	applied	**Crucible :**	Concavus Pan Al, pierced lid		

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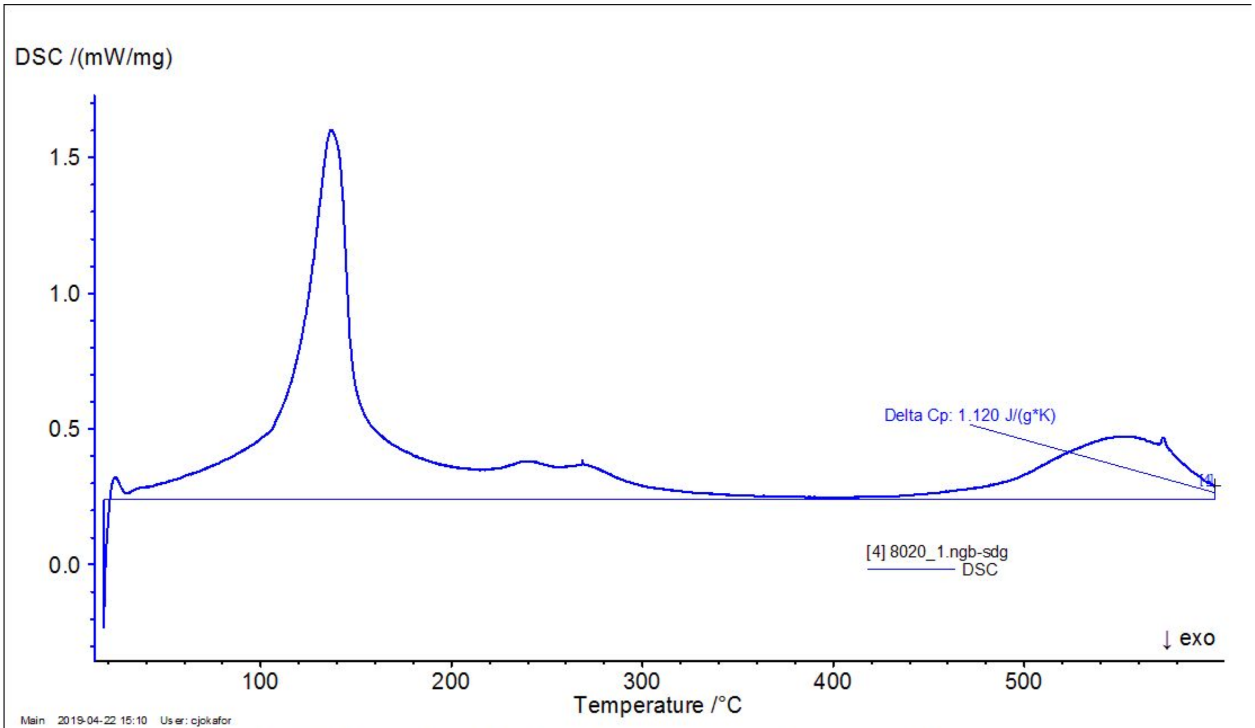

Instrument :	NETZSCH DSC 214 Polyma DSC21400A-0082-L **File :** C:\NETZSCH\Proteus70\data\ClayCement_Mqp\8020_1.ngb-sdg **Remark :** Kwame_RH_Only						
Project :	ClayCement_MQP	**Sample :**	8020_1, 13.8 mg	**Range :**	20°C/20.0(K/min)/600°C	**Atmosphere :**	N2, 20.0ml/min / N2, 20.0ml/min
Identity :	8020_1	**Reference :**	Reference,0 mg	**Sample car./TC :**	DSC 214 Corona sensor / E	**Corr/m. range :**	050/5000 µV
Date/time :	4/22/2019 2:37:21 PM	**Material :**	Powder	**Mode/type of meas. :**	DSC / Sample		
Laboratory :	Soboyejo	**Corr./temp.cal :**	/ applied	**Segments :**	1/1		
Operator :	Chisom	**Sens.file :**	applied	**Crucible :**	Concavus Pan Al, pierced lid		

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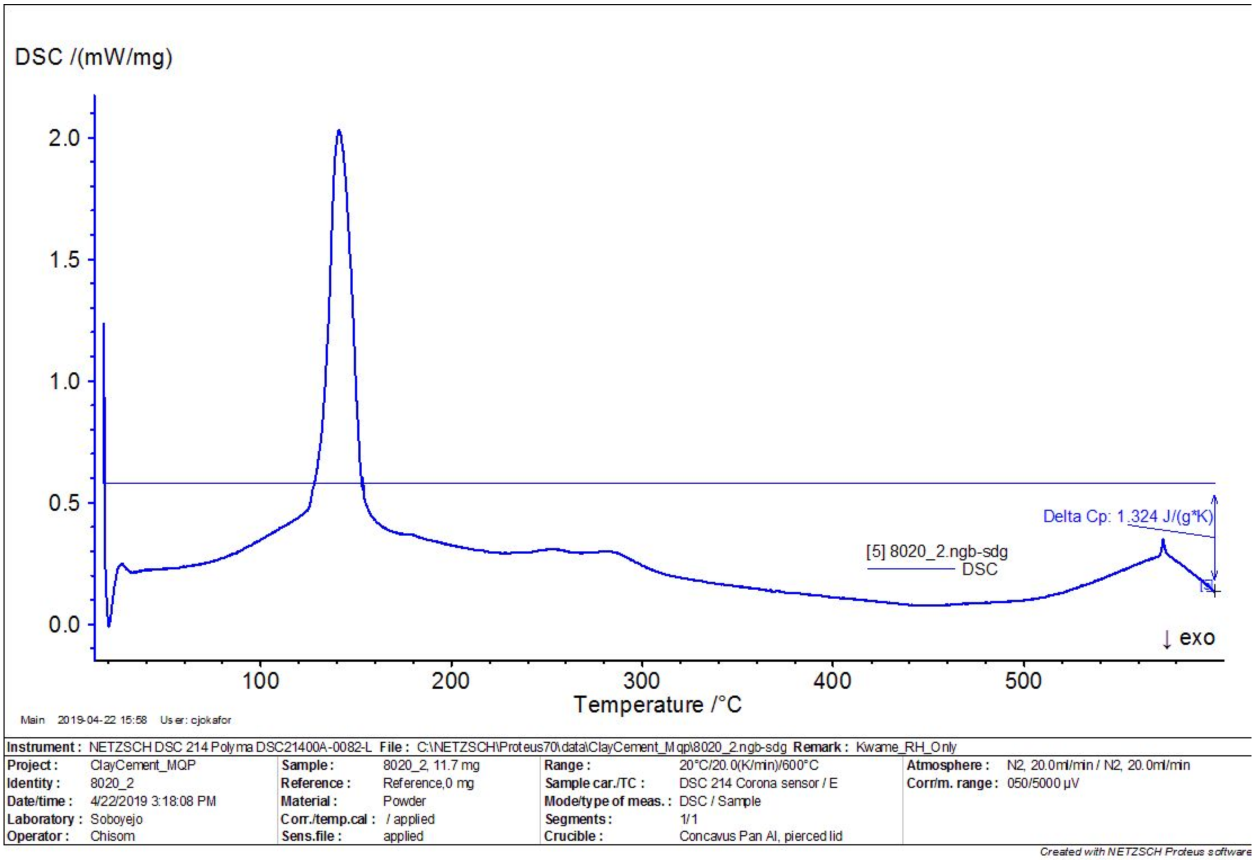
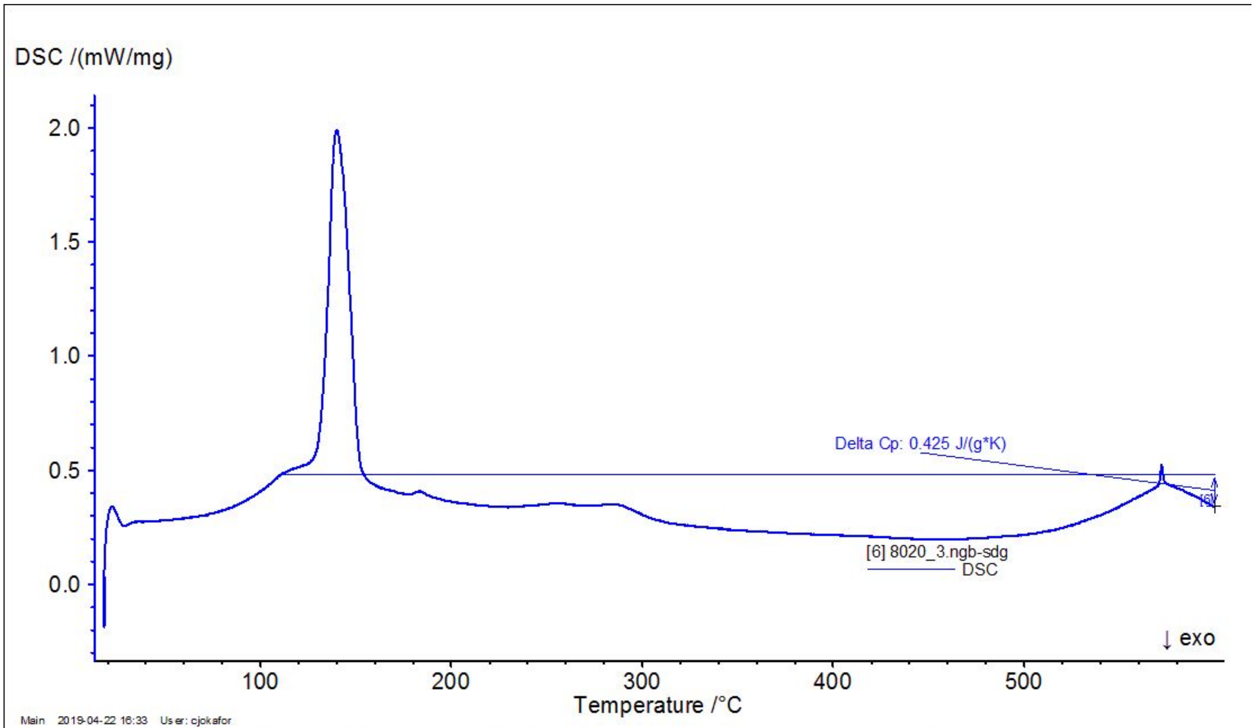

DSC /(mW/mg)
2.0
1.5
1.0
0.5
0.0
100
200
300
400
500
Temperature /°C
Delta Cp: 1.324 J/(g*K)
[5] 8020_2.ngb-sdg
DSC
↓ exo
Main 2019-04-22 15:58 User: cjokafor
Instrument : NETZSCH DSC 214 Polyma DSC21400A-0082-L File : C:\NETZSCH\Proteus70\data\ClayCement_Mqp\8020_2.ngb-sdg Remark : Kwame_RH_Only
Project : ClayCement_MQP
Identity : 8020_2
Date/time : 4/22/2019 3:18:08 PM
Laboratory : Soboyejo
Operator : Chisom
Sample : 8020_2, 11.7 mg
Reference : Reference,0 mg
Material : Powder
Corr./temp.cal : / applied
Sens.file : applied
Range : 20°C/20.0(K/min)/600°C
Sample car./TC : DSC 214 Corona sensor / E
Mode/type of meas. : DSC / Sample
Segments : 1/1
Crucible : Concavus Pan Al, pierced lid
Atmosphere : N2, 20.0ml/min / N2, 20.0ml/min
Corr/m. range : 050/5000 µV
Created with NETZSCH Proteus software



Instrument : NETZSCH DSC 214 Polyma DSC21400A-0082-L File : C:\NETZSCH\Proteus70\data\ClayCement_Mqp\8020_3.ngb-sdg Remark : Kwame_RH_Only

Project :	ClayCement_MQP	**Sample :**	8020_3, 13.4 mg	**Range :**	20°C/20.0(K/min)/600°C	**Atmosphere :**	N2, 20.0ml/min / N2, 20.0ml/min
Identity :	8020_3	**Reference :**	Reference,0 mg	**Sample car./TC :**	DSC 214 Corona sensor / E	**Corr/m. range :**	050/5000 µV
Date/time :	4/22/2019 4:00:54 PM	**Material :**	Powder	**Mode/type of meas. :**	DSC / Sample		
Laboratory :	Soboyejo	**Corr./temp.cal :**	/ applied	**Segments :**	1/1		
Operator :	Chisom	**Sens.file :**	applied	**Crucible :**	Concavus Pan Al, pierced lid		

Created with NETZSCH Proteus software