Feasibility of Translating Earthships in Africa and Future Design Considerations

by

Sade Kailani Nabahe

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2017

Signature of Author .... Signature redacted ....
Department of Mechanical Engineering
May 24, 2017

Certified by .... Signature redacted ....
Maria Yang
Associate Professor of Mechanical Engineering
Thesis Supervisor

Accepted by .... Signature redacted ....
Rohit Karnik
Associate Professor of Mechanical Engineering
Undergraduate Officer

Feasibility of Translating Earthships in Africa and Future Design Considerations

by

Sade Kailani Nabahe

Submitted to the Department of Mechanical Engineering on May 25, 2017 in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

ABSTRACT

Earthships are passive solar buildings with renewable power, water harvesting, and sewage systems, designed to be off grid with minimal reliance on public utilities, and use recycled and natural materials. Due to high initial capital cost and resources needed, earthships have primarily been implemented in developed countries. However, the self-sufficiency earthships offer through their subsystems presents an opportunity for resource-constrained environments. Three earthship projects have been developed in Africa, each serving a unique purpose and overcoming different obstacles. Through earthship design principles, technical reports, and lessons learned from each project, this paper aims to outline design considerations for those who are interested in implementing an earthship in Africa.

Thesis supervisor: Maria Yang

Title: Associate Professor of Mechanical Engineering

Acknowledgements

The author would like to thank the thesis supervisor Associate Professor Maria Yang at MIT; Pema Clark, Shannoh Kandoh and Sam Elliot from the Goderich Waldorf School; Shanil Samarakoon from the Kapita Community Center, and Ludwig Everson from the Aardskip earthship project for the information and pictures given on their respective projects.

Table of Contents

List of Figures

Chapter 1

Introduction

Earthships serve as an alternative to current housing practices, such as the standard wooden frame home in many developed countries and mud bricks in other parts of the world. Earthships are meant to turn waste into building materials while producing electricity, collecting water and managing sewage. This section will detail the design principles, design benefits and drawbacks, and an overview of the projects within Africa.

1.1 Earthship Background

Earthships are passive solar buildings with renewable power, water harvesting, and sewage systems, designed to be off grid with minimal reliance on public utilities, and using recycled and natural materials (Hewitt & Telfer, 2012). Architect Michael Reynolds began to develop the idea in the 1970s with the goal of creating a sustainable structure out of materials that otherwise would have been thrown away. The idea has iterated over the past few decades to improve its functionality in order provide the resident with everything he or she would want to rely on. Earthships are designed with important principles to meet human needs through (Reynolds, 1991):

1. **Naturally regulated thermal heating and cooling systems** through the use of earth-packed tires or earth-filled bags that store the sun's heat during the day and release it during the night. This reduces the need for energy-intensive heating systems and reduces one's electricity bill and associated carbon emissions.

2. **Harvesting of energy from clean renewable sources** through photovoltaic solar panels, wind turbines and/or small hydroelectric river dams. This is dependent on the earthship's physical location, as certain areas will be more suitable for specific sources of energy than others.

3. **Separating, storing and treating sewage** to prevent cross-contamination with food and water sources while the breakdown occurs, resulting in plant byproducts that can be utilized in the garden. This also reduces dependence on public sewage infrastructure that may not be available in some parts of the world.

4. **Utilizing natural and recycled materials** to reduce the emissions produced during construction and exploit existing resources such as dirt, bottles, and tires. The conventional earthship design is known for its earth-packed tires that create the outer walls of the earthship and recycled bottles that create beautiful inner walls.

5. **Water harvesting and recycling** with rainwater collection systems. This reduces dependence on external water supply, relying on what the earth provides. Full or partial dependence varies, based on the specific climate and geographical location. To fully utilize the precious resource, grey and black water systems are implemented.

6. **Food production** in the small greenhouse outside of the main occupancy quarters, where grey-water and treated sewage waste is used to maximize output. The amount of dependence will vary with climate and the number of people that will rely on it.

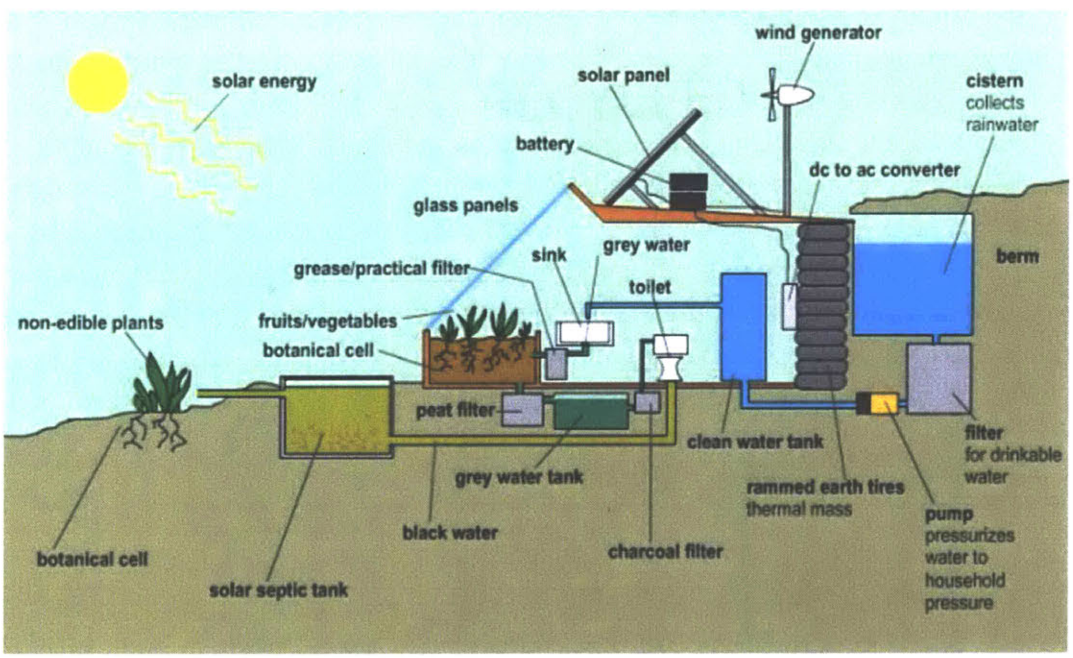


Figure 1a: Earthship illustration showing how all the important subsystems interact to meet human needs and be self-sufficient (earthships, 2013).

There are numerous benefits to the earthship concept. By providing homeowners with food, water and shelter without reliance on conventional infrastructure managed by utility companies, earthships give people self-sufficiency (Hewitt & Telfer, 2012). Its sustainable design reduces the user's carbon footprint by making use of renewable energy sources, building with recycled materials and growing one's food. Earthships can be made from local materials such as clay and earth, or waste like aluminum cans, cardboard, and tires. The flexibility in materials opens up the opportunities for people of different backgrounds to find a fit. Additionally, an earthship is easy to alter in order to meet user needs. Over time the design has been improved to meet such specific needs and adapt to its surrounding environment. Earthships can be used as schools, community centers, information centers, and family homes, and can be located in various parts of the world. Despite the high upfront costs, earthships have long-term financial savings from not paying monthly rent and electricity and water bills.

While there are a number of benefits with the earthship, there are also drawbacks ("Earthship Academic Research Overview, in Plain English," n.d.). Earthships still continue to face difficulties depending on the intended use and geographical location. One of the biggest complaints is thermal performance. In cooler climates, earthships cool beyond occupants' comfort and in warmer climates the heat can reach uncomfortable temperatures. This is no surprise, as the original design was made to withstand the New Mexico climate (Hewitt & Telfer, 2012). While Reynolds and his supporters say that the earthship can be modified to fit any climate, a solution to heat regulation is much needed. Additionally, the high initial capital cost and time required for purchasing the materials, supplies and labor to construct the building limit the number of people who can afford the project upfront. This might be one of the reasons why earthships have been primarily implemented in developed countries and only rarely in emerging economies. And lastly, depending on the country and specific region, utility and land regulations discourage the very principles that the earthship was built upon. For example, when Michael Reynolds and his first team began building an earthship community in Taos, New Mexico, the government required the group to pay for the electricity and water utilities that were not being used, so that the government would not be liable for any unsafe water supply problems that home water collection presented (Hodge et al., 2008).

1.2 Existing Projects in Africa

Due to high initial capital costs, earthships have been primarily developed in the United States, Europe, and Latin America. To date, there are 30 recognized earthship projects around the world ("Earthship | Grand Central," n.d.). While Earthship Biotecture only recognizes two projects in Africa, there is an additional one that was designed by a local architect in South Africa ("Way Off The Grid," 2015). For the following three countries, each earthship has served a different purpose:

1. Sierra Leone –Goderich Waldorf School (Earthship Biotecture)
2. Malawi – Kapita Community Center (Earthship Biotecture)
3. South Africa – Project Aardskip (Independent)

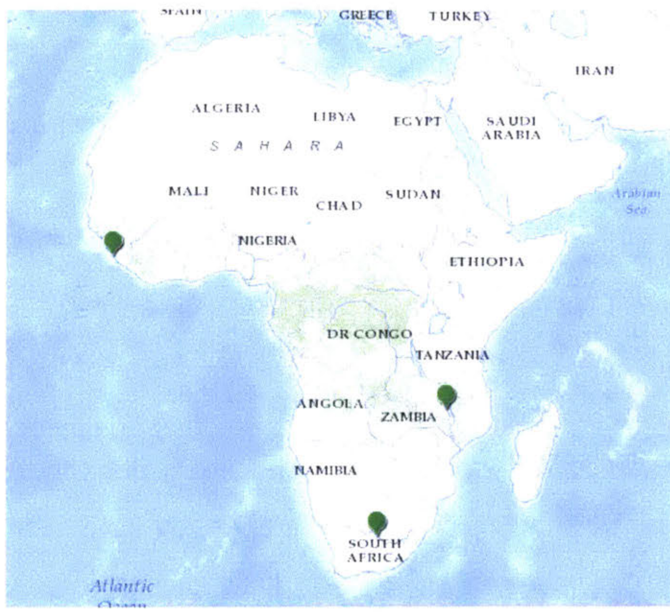


Figure 1b: A map of the three locations for the earthships built in Africa. Earthships were built in Sierra Leone, Malawi and South Africa, each serving a different purpose for the community ("Earthships in Africa," 2017).

There are many challenges still to be resolved, but earthship enthusiasts continue to learn by doing and improve the various earthship subsystems. Earthships present a unique opportunity to Africa, where there is a lack of quality housing. Today homes are primarily built out of mud bricks or concrete and serve only as a place to protect one from the elements (Zeleza & Codesria, 1997). There often are no heating or cooling systems, no reliable electricity and only rudimentary restrooms. Earthships can offer an alternative to current methods for homes or connect communities as village centers.

Chapter 2

Case Studies

Earthships are designed and modified for different environments and purposes. The three earthship projects in Africa all have different use cases, vary in size, and utilize whatever resources are available in the surrounding region. These three stories will give a better understanding of what is required to implement earthships in resource-constrained countries and how the process can be improved on in the future. This section will cover the background information, construction process, and challenges for each African earthship project.

Methodology

For this chapter, the author conducted interviews with the project leader for each African earthship project to gain insight of the building experience and associated challenges. The interviews were conducted through different mediums including email, Skype, and fillable Google documents. Each subject was asked the following questions:

1. How was the project first started and can you give the most recent update on it?
2. How was the location selected?
3. What were some of the challenges that the team faced in regards to design, during construction, material collection, and post construction maintenance?
4. How did you collect all the needed materials? Do you have a final count of the total materials used?
5. Did you install any renewable energy technologies?
6. Is the water collection system meeting everyone's needs? Have there been any issues with sanitation?
7. Were there any government regulations you dealt with (housing, land, etc.)?
8. Who helped build the earthship (volunteers, hired locals, etc.)? What was the final cost and how do you think it could be reduced if possible?
9. How has the project impacted the community? What were their responses throughout the project and how has it changed since it was finished?
10. What do you think could be improved on in the future? Do you think there is anything standing in the way for more earthships to be developed in other parts of Africa?

Responses and information found online were then used to tell each story and develop recommendations for future earthship designers. The respective earthship project leaders have verified all of the following information.

2.1 Goderich Waldorf School, Sierra Leone

The Goderich Waldorf School is located in the Rokel Community, located 14 km east of Freetown in Sierra Leone ("Goderich Waldorf School," n.d.). In 2002, Shannoh Kandoh began teaching classes to child soldiers and displaced orphans on the beach using tarp huts on the shore (earthships, 2012). To encourage the kids to attend, the school donated food and shelter in the hut for the night if they came to class and learned. This took a large number of kids out of undesirable situations, but soon became too crowded. However, with the support of the Dhana Trust in the United Kingdom, the school was able to get help from Michael Reynolds. The earthship project started in October 2011, when Reynolds and his Earthship Biotecture team traveled to help train and build a portion of the earthship, leaving the rest of it to be completed by the locals ("Goderich Waldorf School," 2012). This was the first time that Reynolds and his team ever started a project and did not finish alongside their partners.

The construction attracted 27 interns from around the world and 40 local volunteers that were relatives of the school children. An internship was created to draw in more community interest and paid laborers that would continue the project once the Earthship Biotecture group left. As seen in Figure 2a, the Goderich school was shaped like a flower with six petals that would serve as classrooms (Eke, 2011). Each classroom has the capacity to accommodate 35 children, totaling to almost 200 children (earthships, 2012). Reynolds and his team were able to train everyone in 10 days and completed two out of the six petals with working plumbing and power in place.

For construction, Goderich Waldorf School utilized recycled bottles, rebar, and cement for the classroom walls. The school partnered with a local dump owner to help separate the materials needed for the building (Kandoh, Clark, & Elliot, 2017). In terms of the energy and water systems, the project was planned to include lighting for the classrooms and a pump powered by solar panels. The school was also equipped with a restroom containing a flushable toilet and a sink with water supplied by a roof collection system. With an extreme rainy season in Sierra Leone, the Goderich Waldorf School allows enough water to be stored and used by its occupants for the remainder of the year (earthships, 2012).

Surprisingly, there was no pushback from the government or problems with regulations. The earthship project came at a great time for the Goderich Waldorf School, since they had been threatened with closure if a permanent structure was not completed. Only encouragement was seen from the government, as they were interested in having this be a model for future schools. However, there were challenges that arose post-construction (Kandoh et al., 2017). There were complaints of a strong toilet odor because of the close proximity to the classrooms. Additionally, rainwater penetrated through the concrete roofs and decayed the wooden doors. While the structure serves as a home and learning center for the children, there are concerns that the design may not be adequate to withstand floods, repel rain, or have proper ventilation during the dry season.

Figure 2a: Goderich Waldorf School in Sierra Leone (Eke, 2011).

The school staff and those who were involved in the project made the following observations from the earthship project:

1. **Security was and is the biggest challenge.** The panels were an absolute necessity to the school but attracted thieves when the building was not fenced. This forced the school to hire security that would watch the earthship at night.
2. **It was difficult to collect the right number and size of materials.** The earthship design required large numbers of plastic bottles, cans and tires. It was particularly difficult to get the exact same sizes of tires to make construction easier, forcing the team to spend long periods of time sorting. Kandoh recommends at least two months are needed to collect materials, clean and prepare for use (Kandoh et al., 2017). Kandoh also added that the time and money needed to collect waste materials have prevented neighboring communities from applying an earthship in their village despite their great interest.

3. **Hands-on-training sessions were short.** Reynolds and his team had a short visit due to financial constraints, forcing them to conduct the training within 10 days. Together, everyone was able to build two out of the six rooms, and when Reynolds left, those who remained were still able to reach him for help. However, this was not as easy as having Reynolds and the team located on-site.

The Goderich Waldorf School is now completed and continues to serve the children in the Rokel community.

2.2 Kapita Community Center, Malawi

The Kapita Community Center is located in Kapita, Malawi, and led by the nonprofit Empower Projects, which works on a number of sustainability and development initiatives in the area ("Earthship Community Centre," n.d.). The project was started in 2013 with the vision to create a more sustainable and functional structure that could serve a number of communal needs. The region was selected in a rural disenfranchised region that was selected during a previous scoping exercise that considered energy, water and financial service access within the community (Samarakoon & Ntaukira, 2017). Kapita is a poor isolated region with 38 villages holding a total of 5,000 people who are primarily subsistence farmers and live on less than $0.80 per day ("Earthship Malawi - Kapita Community Centre," n.d.). Kapita did not have a community space to house key services that the village needed and saw the earthship as an independent regional hub for development.

Empower Projects drew on expertise from Michael Reynolds and the Earthship Biotecture team. After selecting a site and working with Earthship Biotecture to finalize a design, over 80 volunteers from around the world trekked to Malawi in October 2013 ("Earthship Malawi - Kapita Community Centre," n.d.). The international volunteers each paid $1000 to participate in the project and that money was used to pay for the Earthship Biotecture team to travel to the site for two to three weeks (Samarakoon & Ntaukira, 2017). Michael Reynolds and his team trained and helped the volunteers and local community members to build two out of the eight rooms in this time. This allowed them to demonstrate how to construct the earthship and give the local community the tools to complete the rest without the Biotecture team there.

Figure 2b: Community members and volunteers with the almost completed Kapita Community Center in Kapita, Malawi .("Earthship Community Centre," n.d.)

In 2014, the Kapita Community Center still had six more rooms remaining to be built ("Earthship Malawi - Kapita Community Centre," n.d.). However, one of the already completed rooms was used by the Zatuba Community Bank to serve its customers. At that time, Empower Projects raised $17,500 in outside donations to buy and transport the building materials that were unable to be sourced locally. These materials included: cement, rebar, wire, gravel, solar panels, water tanks and piping.

Employing a common earthship design, the Kapita Community Center used earth-packed tires complemented with traditional adobe building techniques. For the roof and the inner walls, boys from the local community were hired to source recycled bottles from collection centers in the capital, Lilongwe (Samarakoon & Ntaukira, 2017). The Kapita Community Center has a rainwater harvesting capacity of 12,000 L, composting toilets for sustainable waste management, self-contained grey-water and black-water systems, and an organic food garden. The center was equipped with a solar system to light and charge electronic gadgets. As seen in Figure 2c, the Kapita Community Center features a seed bank, library, kindergarten, community radio station and meeting hall along with 6 toilets and 2 showers ("Earthship | Africa," n.d.).

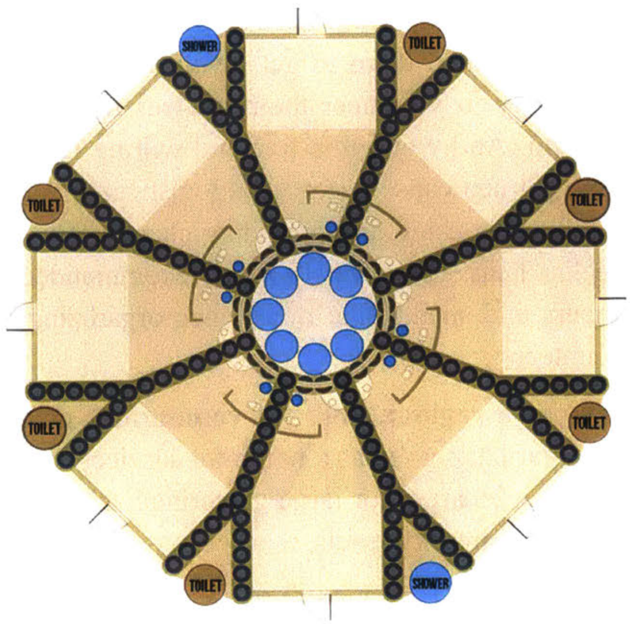


Figure 2c: The Kapita Community Center floor plans, showing the 8 rooms, 6 toilets, and 2 showers that serve as the regional hub for development. In the center, there are water storage tanks. The rooms serve as a seed bank, library, kindergarten, community radio station and meeting hall. ("Earthship | Africa," n.d.)

Although the center has been successful, it did face some challenges both during and after construction (Samarakoon & Ntaukira, 2017). During construction, there was a lack of local resources nearby, forcing the team to transport almost all needed materials 400 km away from Lilongwe. The design also relied heavily on cement, causing the cost of the earthship to rise beyond the community's capacity, so that they were unable to finish building the center on their own. Empower Projects additionally faced logistical problems for the large first round of volunteers who were there for 2 weeks.

Empower Projects and those who were involved in the project made the following observations and recommendations for future earthship projects:

1. **Cement is an expensive commodity in Africa.** Cement offers a quick, structural solution for earthship construction. However, the high cost compared to building conventional brick and mortar houses discourages poorer communities from its use. Furthermore, the use of cement should be decreased, as it is not a sustainable building material and has many negative environmental effects.

2. **Too much help can be overwhelming.** Earthships have attracted the attention of many around the world and motivated them to get involved in any way possible. People are jumping at the opportunity to volunteer their services to learn and gain experience in constructing an earthship. And while this free and willing labor is helpful in areas with less financial resources, it can cause unforeseen logistical challenges. Empower Projects faced problems in feeding, housing and providing clean water for the 80 volunteers that were there for 2 weeks. Thus, Empower Projects recommended that any future projects limit volunteer numbers and spend time in advance organizing shelter, food, and water systems for their volunteers.
3. **Earthships can serve as a regional hub for community meetings and services.** The Kapita Community Center has served as a home for services that the community needs. It provides a central meeting location for large gatherings, a way to connect with a bank, a place to learn, and store community assets.

Currently, the Kapita Community Center is 90% finished, with only flooring to be installed in four more rooms. The women in the village, according to the common practices, will use clay to do the flooring for the remaining four rooms. It is expected to be completed by June/July of 2017.

2.3 Aardskip Earthship, South Africa

The Aardskip earthship is located on the outskirts of the small town of Orania in South Africa ("Way Off The Grid," 2015). The project was started in 2011 by Ludwig Everson, who first learned how to build earthships in the Netherlands and then moved back to South Africa to experiment on his own in an Afrikaans community (Everson, 2017). As seen in Figure 2d, the Aardskip features 3 bedrooms, 2 bathrooms, a study room, dining room, and kitchen (Everson, 2009). It serves as both a home and a training center to teach other South Africans about the principles of sustainable building design.

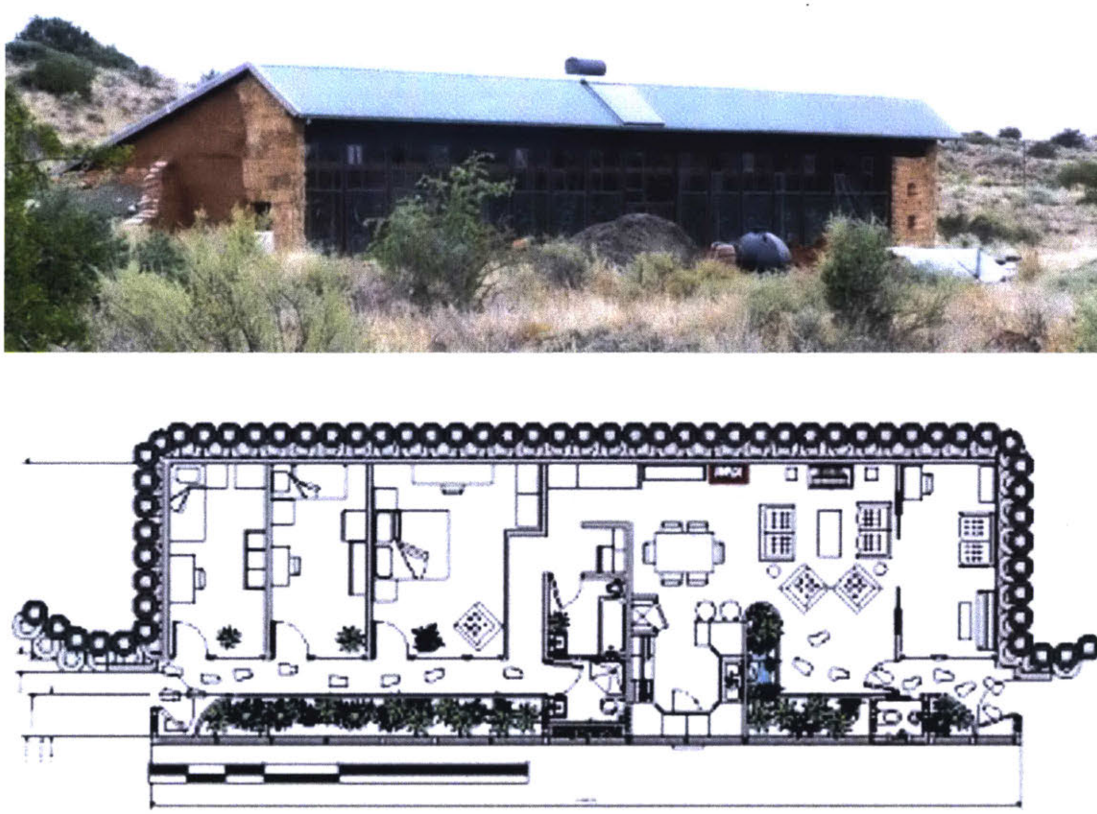


Figure 2d: Top Image: Aardskip earthship exterior ("Way Off The Grid," 2015). Bottom Image: Original Aardskip floor plans illustrating three bedrooms, two bathrooms, a study room, a dining room, a kitchen and information center room where earthship trainings are held to the community (Everson, 2009).

With a hybrid design, the Aardskip uses earth packed tires for the foundation, earthbags for the outside walls, and bottles for the inside non-weight bearing walls (Everson, 2017). The biggest distinction of the Aardskip earthship is its large use of earthbags. Everson chose to use earth-bags for the structure because few tires were available in rural areas and Everson could easily source bags from farmers. Everson and his team utilized the dirt close to the site so it made logistical and financial sense to use the bags over tires. The team also discovered that earthbags were much easier to compact over the tires. Packing tires with dirt is a tiring task that can require more than one person to fulfill unlike the earthbags, which need only one person to put the earth inside. By the Aardskip construction site, the soil had 10-20% clay content that improved the building's ability to repel rain. However, earthbags cannot be used universally because the correct dirt composition must be used. For example, river or beach sand is not suitable for outside plastering as it is more prone to leaks.

Everson and his family began using a generator to supply energy for their home, but then transitioned to photovoltaic panels (Everson, 2017). The Eversons installed 2kW panels that can produce up to 11.5 kWh/day to meet their needs, but found they still had to change their high-energy use habits. The Eversons decreased their electrical consumption by reducing the number of appliances in their home to a microwave, two hot plates, convection oven, electric kettle, computer and hair dryer. They also had to adapt to the weather, being careful not to use the high consuming appliances such as the microwave, convection oven and electric plates during cloudy days. The Eversons supplemented their total energy supply with 2 kg of gas for the year to heat water and another 9kg for the hot plates. Everson plans to add a biogas digester to further decrease outside energy dependence.

The Aardskip contains a rainwater collection system that contains multiple filters to remove any particulates before the water goes into the tank. The water goes through two particle filters, a carbon filter and a UV filter before consumption. While Everson claims the rainwater in the rural village is safe to drink, he adds additional filters to get the cleanest water possible. The water is recycled further as grey and black water. The grey water is used to water the plants in the small greenhouse and the outside plants use black water after passing through the septic tank.

The Aardskip faced a majority of its challenges during construction with a few more related to general maintenance and utility capacity (Everson, 2017). During construction, the two biggest challenges were gathering materials and finding workers to do the construction. Everson only managed to get enough tires to build the Aardskip's foundation and quickly ran through the local dumping ground's bottle supply within a week to build the inner walls between rooms. Everson said that he attracted some local volunteers for a few days and two long-term volunteers for three weeks, but otherwise had to hire local labor and do it himself. In terms of regulation, Everson did not face much conflict, but the insurance company did require that Everson hire a civil engineer to inspect the Aardskip during construction, forcing Everson to change insurers.

Post construction, Everson did not face any serious problems except heat regulation within the home and one water leak on the eastern side, where Everson had to add an extra water drainage system underneath the floor to prevent the Aardskip from flooding. As expected seasonal changes affected the earthship's ability to regulate its heat. Everson found that adding shade blocks to the windows helped reduce inside temperatures during the warmer months. Everson also added another grease filter to speed up the grey water cell absorption rate. All other general repairs were solved by replacing areas with limestone with concrete and earth to patch up holes.

Upon building his own earthship, Everson learned a lot and made the following three observations:

1. **Even with extensive research, no one can predict what unique problems will arise.** While the earthship concept aims to be suitable to all environments, every earthship will vary depending on the climate and available materials in the area. Each design will present unique problems, which will not be evident until it is fully built. Everson suggests that if one has the time and financial resources, to make and monitor a small one-bedroom earthship over a year as an experiment. This will help to identify design flaws and make improvements for the larger structure. The earthship concept is still being improved over time and any additional information can help future earthship builders.
2. **Utilize local materials and skills.** To maintain the earthship's sustainability, it is important to use materials that are close to the site. It is expected that some materials will need to be outsourced, but one should factor in the financial, time and environmental implications of transporting those resources. Additionally, it is recommended to locate talent from the area of construction to gain more insight for the specific region, local regulations and what available materials can be used. This also presents the opportunity to create jobs in the process.
3. **The earthship's founding principles can be applied together or separately.** To build a full earthship, high initial capital resources are required. This will be a great barrier for poorer communities who do not have the ability to afford one. However, this does not mean that the benefits from the earthship are lost. Subsystems like the water harvesting and recycling can be implemented with or without the earthship. Everson said that after building the Aardskip, nearby community members implemented some of the founding principles such as the grey water system.

Chapter 3

Future Design Considerations

While there are still challenges to overcome, earthships offer numerous benefits to both developed and developing countries. As seen from the case studies detailed above in Chapter 2, earthships' functionality and overall design differ depending based on climate, location in country, available resources, subsystem design criteria, regulation and community engagement. This section will outline some of the design considerations that must addressed for future earthship projects within Africa or other resource-constrained environments. This is not meant to be an exclusive list but a starting point for those interested in implementing an earthship in their community.

3.1 Location and Earthship Siting

There are many factors to be accounted for in earthship siting, such as geography, climate and available resources. Earthships perform differently based on geography and climate influences. To avoid some of the common complaints of earthships, the earthship should be placed according to the climate. Warmer and drier climates have been shown to perform better than cooler and humid weather in theory and practice (Kruis & Heun, 2007). This is not unexpected as the earthship concept was originally designed for Taos, New Mexico. The most complaints have been reported in humid and tropical climates. There have been reports from earthships residents that water can collect along the interior wall surfaces, presenting mold and algae problems ("Earthship Research," 2012). Additionally, too much humidity can result in high rates of condensation in the biocells during the winter. Even in non-humid regions, earthships still have heat regulation issues ("Earthship Research," 2012). In hot areas, earthship residents stated that some rooms over heat, especially the greenhouses that sit at the entrance of the building. Conversely, earthships sometimes have trouble retaining heat so during cooler or cloudy days, residents rely on a back up heating source to keep them warm. However, it should be noted that every person has different tolerances for heat so each experience will vary.

There have been efforts to identify the climates most optimal for earthship performance. One study conducted by Kruis and Huen analyzed four potential locations for earthships within the United States to see if the projects met desired living requirements and compared them financially to a standard wooden frame house (Kruis & Heun, 2007). The four locations and climates tested were Alaska (continental sub-arctic), Michigan (humid continental), Hawaii (tropical wet/dry) and New Mexico (dry, arid). Kruis and Huen built a thermal model using an energy simulation program based on solar radiation, outside temperatures and precipitation rates for each area as well as completed a cost benefit analysis. The study concluded that earthships are feasible in dry, humid continental and sub-arctic climates. It was determined that three out of the four locations were worth implementing in their respective locations based on thermal comfort, electricity usage and finances. Therefore, places with a tropical wet climate like Hawaii are discouraged due to cost and performance. While the study helps to narrow down regions, it is limited in scope as it looks at earthships located in the United States. Additionally, it compared the earthship to a standard wooden frame house, which is not as common as the mud brick houses that are used in Africa (Zeleza & Codesria, 1997).

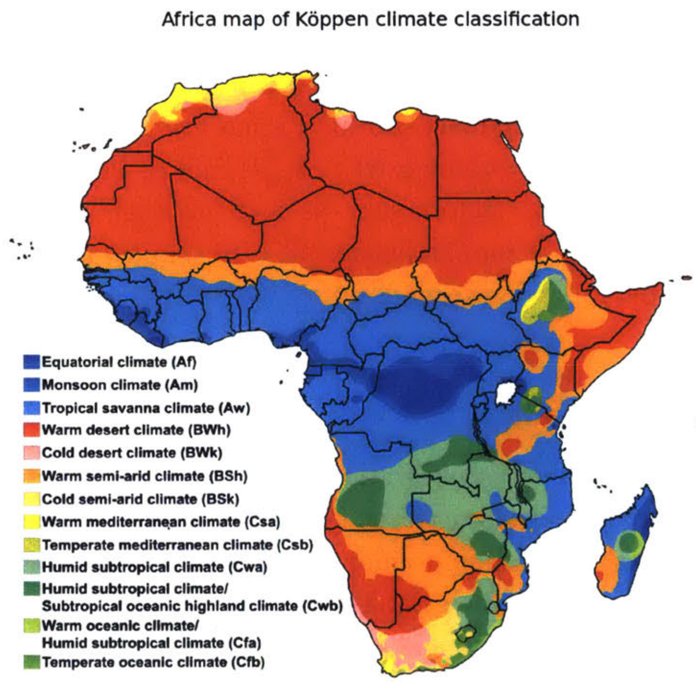


Figure 3a: African climate zones (Zifan, 2016). The highest performing earthships would be located in the most north and south parts of Africa. A study has shown that earthships located in tropical wet regions are not efficient compared to standard wooden houses (Kruis & Heun, 2007). Therefore, the blue and green regions should be avoided.

In designing an earthship for Africa, it is important to identify the different climate regions where an earthship will perform best. Africa is a large continent where some areas will be more suitable for earthships than others. Africa has desert, tropical, semi-arid and humid subtropical climates spread throughout the continent. Based on the Kruis and Heun study and African climate information, the most northern and southern countries are the best-suited locations for earthships. Some countries in these regions include Algeria, Libya, Egypt, Sudan, Niger, Namibia, and Botswana. In looking at Figure 3a, the blue and green regions are to be avoided. However, there will be climate variation within the country. Therefore, it is recommended to conduct a climate specific study for the country of interest to identify the most optimal locations. It should be noted that earthships can exist in humid and tropical regions, but will have to overcome additional obstacles that climate brings.

Other siting considerations include angle of direction and placement relative to geographical barriers (Reynolds, 1991). Geographical location and climate are closely related as these have a large influence on how the earthship operates. For example, it is important for the earthship to be facing the sun at the correct angle relative to where it is located in the world. In the northern hemisphere the row of windows are directed towards the south in order to capture the most sun and vice versa. Placement depends on other geographical factors such as mountains or valleys, making sure that the earthship is not in danger of being affected by the landscape. It is suggested that earthships are placed on a slope and face the sun for most of the day in order to avoid being flooded at the bottom of a hill as well as gain extra heat (Reynolds, 1991). The earthship site will also be dependent on other outside factors such as material cost, availability and potential renewable energy resources. Each factor can impact the earthship's viability and therefore these subjects will be covered in the following sections.

3.2 Construction and Materials

Another design consideration is the utilization of available resources. The designer must identify what and how many materials are needed to construct the earthship for its designated purpose. However, earthships require large amounts of materials that may be unfeasible for implementation. For example, the Brighton Earthship in the United Kingdom alone used 2 tons of cans and bottles, 1500 cardboard boxes, and 1000 car tires. This will affect the final earthship design, limiting the designer to use materials available in the community and surrounding region.

For a 2,000 square foot earthship will use approximately 1,000 tires for the building's structure and foundation (earthships, 2015). Tires provide thermal storage and regulation for the earthship as well as durability (Hewitt & Telfer, 2012). However, the large number of tires required can be difficult to source depending on the area of implementation. As told by every earthship project in Africa, tires were very difficult to find and transport to site. Like the Aardskip project, designers may find it difficult to source enough tires, thus limiting its use to just the earthship foundation or looking to alternative construction methods such as earthbags. The designer may additionally face insufficient supply of recycled bottles and cans for the inner earthship walls as a single project can quickly use up local resources, forcing designers to look to other areas.

In earthship construction, the designer should analyze current waste management and recycling systems. This will help to identify what can be leveraged to build an earthship. As seen from the Aardskip, partnerships are beneficial to make between recycling and waste collection centers. Although it should be noted that there could be government regulation on how waste can be used, potentially impacting earthship construction. For some earthships in Europe, it was reported that the government had waste handling and storage rules that were initially difficult to overcome. For example, the Earthresidence project in Belgium was not allowed to use tires as a construction material, forcing them to use earthbags instead (Hewitt & Telfer, 2012). Each country may have different standards on what is considered to be waste and what restrictions are placed over it. So while reusing old bottles and cans is reducing trash in the waste collection centers and reducing carbon emissions, it is important to abide by the any laws.

Even if materials are available for use, the designer should consider the cost of materials and transportation required to bring the materials to the construction site. The designer should calculate how much energy it requires to transport the materials and estimate the carbon emitted in transportation and its related carbon emissions. The earthship material-recycling concept is meant to make use of existing materials and avoid producing additional carbon and other harmful emissions in new material manufacturing. Therefore the most environmentally friendly option should be selected. If the carbon emitted is greater than manufacturing new materials, the designer should reconsider and try to identify a new solution. As seen in section 2.3 in the Aardskip project, Everson found that transporting tires from the nearest town would be difficult and not cost effective. Therefore, Everson decided to use earthbags instead because of its ease in transportation and ability to source the cloth bags.

3.3 Subsystem Design

Earthship's subsystems provide residents with a lower carbon footprint, independence from large-scale utility networks and long-term financial savings. The subsystems include: renewable energy, water collection, sewage treatment, and food production. This section will outline the design considerations for each subsystem and its potential role upon implementation in Africa.

3.3.1 Renewable Energy

It is estimated that 16% of the global population still lacks access to electricity, 95% of which are located in Sub-Saharan Africa and developing regions in Asia ("WEO - Energy access database," 2016). Two thirds of people in Sub-Saharan Africa lives without power and are primarily located in rural areas ("WEO - Africa focus," 2014). This limits economic growth, medical care, and education within the regions. Earthship's renewable energy systems have the power to bring electricity to some areas in Africa and aid in future community development.

Electricity demand and potential renewable resources are the two biggest design requirements for the earthship's energy system. When choosing a location, potential renewable energy resources should be identified to determine the energy system. Earthships commonly utilize at least one of the following renewable technologies: photovoltaic solar panels, small-scale wind turbines, and micro hydro dams (Reynolds, 1991). Wind and micro hydro are typically more location specific and dependent on particular topography, requiring consistent strong winds and small rivers nearby respectively. Therefore, solar is the most popular source of energy since it can produce sufficient electricity without full system optimization. However, there are simple design measures that can be added to improve overall performance (Hewitt & Telfer, 2012). For instance, facing the panels and earthship in at a particular angle towards the sun, by adjusting for latitude and the changing seasons. By optimizing the system, the designer will increase output and potentially lower the number of panels used and cost associated with installation.

As a critical subsystem to the earthship, the renewable energy potential in Africa should be explored. The solar potential for the African continent is shown below in Figure 3b, where the most northern and southern regions have the potential to produce most power. This aligns with the same regions that were most conducive to earthship performance based on climate. Fewer panels will be needed to produce the same amount of power relative to low solar resource regions, saving the designer money. However, the designer should consider other renewable sources as well. For more information on the wind potential distribution within Africa, see Appendix I.

In determining the size of the system, the designer needs to estimate the total electricity demand. This will vary according to the purpose of the earthship. For example, an earthship used for community meetings might use less power than an earthship residence with a family who uses large appliances. The designer will need to consider the potential size of the building, number of users, and all installed electronics. This is seen in Empower Project's recommendation to consider the community's interest such as the desire to charge cellphones with the available electricity. While this takes only a small amount of energy, a high number of customers will require a larger energy system.

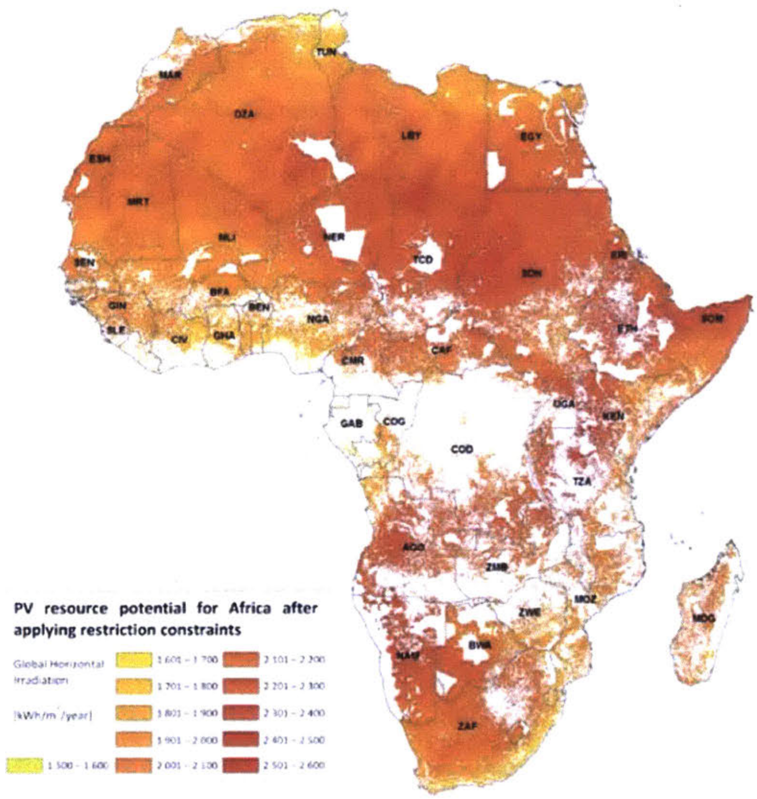


Figure 3b: Africa's potential photovoltaic resource (IRENA, 2014). The most northern and southern regions of Africa have the highest photovoltaic potential for earthships, offering a reliable energy resource.

Additionally, the designer will need to account for renewable energy variability. One of the drawbacks about renewable sources is inconsistent energy production. This can present situations where the solar panels output high levels of power during peak hours when there is low demand and leave people with little power during low production hours. To mitigate, battery storage is recommended to store excess energy during high-energy production hours. However, this comes with additional costs and maintenance for the batteries that resource-constrained communities most likely cannot afford. Storage is not absolutely necessary but will require users to adapt their electricity usage behavior based on the weather. In acclimating to the Aardskip, Everson and his family were careful not to use energy intensive appliances during cloudy days and instead relied on their back up gas stove. Everson reports that it did take some adjustment at the beginning when his family was not used to these energy saving techniques, but now say that they rarely exceed the energy generated from their panels.

Renewable energy sources will also require high initial capital. Earthships are estimated to require 10% greater initial capital investment than conventional homes (Teddington, 1999). This will require the designer or project manager to create a financial plan. While both the Goderich Waldorf School and Kapita Center were reliant on outside donations, there may be opportunities to utilize other resources such as micro financing, grants or pooling together community resources. However, the price of solar panels is decreasing significantly each year, which will make it easier to invest in the future.

However, photovoltaic panels offer much value to earthship residents and thus could present potential security issues. Everson did not experience any theft attempts since the Aardskip was located in a safe community, but the other two projects reported issues. Four of Goderich's panels were stolen in the rainy season. Goderich staff found it hard to protect the panels since the earthship was located in an open field where unemployed youth were scouting for valuable assets and ultimately made the Goderich staff decide not to install the original designed solar pump system. The Kapita Community Center faced two cases of theft where solar panels, batteries and other tools such as hammers that were stolen from the building. Since then they have hired a security guard at night to reduce the future attempts. Therefore, the designer should take into consideration the safety of the community and whether the valuable earthship subsystems are at risk of getting stolen.

3.3.2 Water Collection and Sewage Treatment

The World Health Organization reports that at least 1.8 billion people around the world use contaminated water sources that can transmit harmful diseases ("WHO | Drinking-water," 2016). However, the areas that need the most improvement are within Africa and Asia. In Sub-Saharan Africa, 319 million people still lack access to drinking water, forcing them to turn to unsafe practices ("WHO | Key facts from JMP 2015 report," 2015). Earthship's rainwater collection systems have the opportunity to provide a source of clean water for communities and improve the quality of life.

Water collection systems are essential to the earthship design and to the users relying on it. Like renewable energy, rainwater collection systems dependent on weather conditions. As seen in Figure 3c, precipitation rates vary across Africa (Delphi234, 2014). Areas with high rainfall will provide a more secure water supply for both earthship residents and the installed greenhouse. Earthships are designed to provide enough water to survive in any region of the world where annual precipitation is 200 mm (Hewitt & Telfer, 2012). However, this is dependent on how much and how often the water is being used. In planning the water collection system, the designer will need to determine the average volume of water consumed in a day and how it relates the earthship's collection potential. The collection potential can be calculated based on the size of the roof and factoring in losses from evaporation. Therefore, the designer will have to balance demand and supply based on the earthship's designated purpose.

However, there is a tradeoff between earthship performance, renewable energy potential and water supply. While central and western Africa has a more secure water supply from rainfall, its humid and tropical climate are not conducive to earthship performance. This region also has low photovoltaic potential, requiring a larger system to provide power for the earthship. In contrast, the northern and southern regions of Africa have high renewable energy and earthship performance potential, but low precipitation rates, limiting water usage. Depending on the area of implementation, the earthship will limit how much the users can rely solely on its energy generation or water collection.

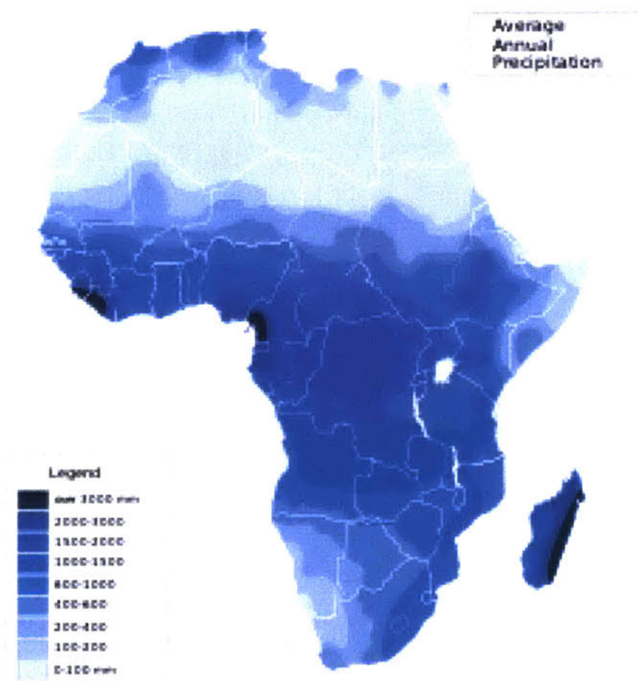


Figure 3c: Precipitation rates in Africa (Delphi234, 2014).

While 83% of water used by the average consumer does not need to meet drinking quality standards, designers will need to ensure that the water collected and used for drinking purposes is safe (Hewitt & Telfer, 2012). For drinking water, the designer should ensure that it meets the World Health Organization water quality guidelines (World Health Organization, 2011). Water quality will be contingent on where the earthship is located. Urban areas have higher levels of air pollution that can affect rainwater quality, possibly requiring additional treatment compared to rural areas. Regardless of location, the designer should conduct water quality tests to ensure that the water does not have dangerous levels of contaminants and is safe to consume. Further treatment may be necessary if taste is also important to consumers.

The remaining water supply can be used for other domestic purposes and then be later recycled as grey and black water. Earthship's grey-water recycling system harvests and treats water that flows from sinks to water plants and flush toilets (Reynolds, 1991). Additionally usage is referred to as black water, which is recycled for human waste purposes. This water is separated from in septic tanks and treated by plants outside the earthship. The designer should take extra precautions when designing grey and black water systems, as it can present health hazards if mixed with drinking water. However, reusing water especially in water scare areas, will allow users to fully utilize the valuable resources for other purposes other than consumption.

3.3.3 Food Production

Plants within earthships help to regulate heat and treat sewage. However, the plants that make up the greenhouse can also produce food to feed earthship occupants ("Earthship | Organic Food Production," n.d.). Earthships have the potential to grow vegetables, fruit, herbs and flowers, adding to the earthship's independent and sustainable design. The designer has numerous options of what to grow depending on the local climate, soil quality, and desired uses. Since growing food is location dependent, it is recommended that the designer consult a local expert who has more knowledge of food products that are easy to grow and maintain according to the region.

3.4 Regulation

Depending on the area of implementation, earthships are subject to federal and regional regulations. Before beginning to construct an earthship, the designer should investigate for any housing regulations that must be met before construction. The building will most likely have to pass general building standards. While the published plans from Earthship Biotecture do meet code, any additional modifications should be re-evaluated. Everson experienced this first hand when the Aardskip project was required by the town to have a certified civil engineer monitor its construction for safety. Past regulations have also required earthships meet protocols for solar and wind energy generation (Hewitt & Telfer, 2012). These standards may be more flexible in parts of Africa than in most developed countries, but no assumptions should be made.

Additionally, past earthship projects have been required by the government to pay for electricity and water utilities despite not being connected. When Michael Reynolds and his team built the first earthship community in Taos, New Mexico, the government argued that the community had to pay for utilities to avoid prosecution related to access of clean water, electricity and roads (Hodge et al., 2008). This forced Reynolds and his team to spend the next few years formalizing the earthship community and negotiating utility payments. For the Aardskip project, Everson was faced the same situation when he initially told to pay for water and electrical utilities because there was already infrastructure in place and without connection, it would be put it to waste. However, in the end Everson chose to live on the outskirts of Orania to avoid regulations.

While it depends on project and location, waste management regulations can also prevent earthship implementation. In the United Kingdom, environmental agencies have investigated the environmental impacts associated with building with waste materials before approving construction (Hewitt & Telfer, 2012). There is no agreement on what is defined as waste and what modifications are permitted, causing every earthship to have a unique authorization experience. For example, Earthship Brighton was not granted an exemption or license by the local environmental agency, but was still able to continue as it was seen as a low risk, but innovative project. Since upcoming earthship projects can present questions to laws, it should be expected that regulatory bodies will be slow to change and in making a decision. Depending on the regulatory bodies' capacity, the decision may be pushed to local government approval. However, these questions cannot be answered without involvement of officials within the area.

Earthships may have to meet additional regulations related to water and sewage. In Europe, earthships were required to meet water quality standards for potable and non-potable sources (Hewitt & Telfer, 2012). Water and sewage standards can vary by country or region and therefore, the designer must verify what laws will he or she need to follow. It is recommended to reach out to local governmental officials and environmental agencies to understand all the regulations the earthship must meet.

3.5 Cultural and Social Considerations

For designers interested in implementing an earthship for community development purposes, understanding the region and its culture is important to a future earthship design and success. By identifying the community's beliefs and perceptions, it is easier to identify potential obstacles to implementation. How the designer approaches this depends on whether they are from the area of interest of not. For those that are not from the area of interest, the designer should begin by reaching out to the communities located near the project site. Before even beginning to talk about the earthship, it is important to identify the community's current situation and future aspirations. This will give the designer awareness of whether the earthship and its proposed benefits fit within the community's needs or if another initiative is more suitable.

If there is a fit, the designer needs to understand if people are willing to have and make an earthship. Earthships require high initial capital and time to complete, thus there needs to be strong support from the community in choosing an earthship rather than existing construction methods. However, it cannot be assumed that people will choose the earthship over current practices. Since people have developed particular habits over time, one has to prepare for the chance that people may not be willing to change how they carry out tasks because of what they have been taught for generations. For example, mud bricks have been traditionally used in many parts of Africa (Zeleza & Codesria, 1997). While some are using new construction methods and materials like cement, not everyone will want to change based on the available resources and what they have previously learned. Therefore, in order to motivate people to change, the perceived benefits have to out compete current methods.

Surprisingly, aesthetics could play a large role in the community acceptance. While earthship enthusiasts and environmentalists are attracted to earthship's junk aesthetic, there may be some who are not. In developing countries, aesthetics can be an indictor for wealth. Products that differ too far from what is considered normal in the specific community or do not meet the same standards as in developed countries can be questioned or not used at all. It possible that homes or community centers made from reused materials may not been viewed as green and innovative, but cheap and foreign. Therefore, it is critical that the designer understands how the community will perceive the earthship exterior design

As Everson pointed out, it is useful to connect with a local architect or leader in the community. This will provide the designer with more insight in how the community operates and what the community is willing to offer. The community leader can help identify what systems may be leveraged to construct the earthship such as where to source materials, what is available in the area and who can help support earthship construction. The individual will also have a better sense of what the government might push back on and where further work is not necessary. For those originally from the area of interest will have an advantage so these initial steps towards learning about the community may be already known. However, it is also important to check assumptions and see if earthships can fill the need.

Chapter 4

Recommendations

Earthships have attracted the attention of many across the world. Its numerous benefits offer the opportunity for an improved quality of life, for both developed and developing countries. As illustrated through the stories of existing projects in Africa, earthships can act as a regional center for educational, financial, and social services. This prospect may excite those to bring earthships to their communities or to others.

For those interested in designing an earthship in Africa or any resource-constrained area for community development purposes, there are many elements that need to be considered. As outlined in Chapter 3, the designer will need to take into location siting, available materials, and subsystem design in creating the best performing earthship. However, the designer will also need to think about how the earthship fits into the communities' social structure by understanding government regulations and cultural practices. Both the technical and social aspects of a new earthship project are critical to its success, but it can be difficult to navigate. Therefore, the designer should use the following design framework:

1. **Understand the current situation.**

   It is important to learn about the region and culture for any initiated community development project. This information is not gained from a distance, but by working in the field and engaging in discussion with those who live there. By first understanding the community's struggles, aspirations and structure before starting a project, the designer is able to determine whether earthships are a suitable solution to current problems or if something else is better fitted. The designer will also be able to develop a plan, leveraging local systems in place and/or avoiding potential technical and social obstacles. The goal of this step should be to clear assumptions, determine whether the users want an earthship, and create a building that serves the community's needs.

2. **Select a location based on each of the optimized subsystems**

   After the designer decides that an earthship is suitable for a community, he or she will need to choose a location for the earthship. Placement of the location will be determined based on climate, geography, optimized subsystem design, available materials, and regulatory factors. Factors that affect earthship performance such as climate and subsystem design should be prioritized first. However, the materials that are available in the area will determine the final design, so the designer should identify what he or she can utilize as well as how to transport it to the site.

3. **Organize project execution.**

   Upon determining a site, the designer will have to decide how the project will be financed, find the labor needed for construction, and verify that the earthship meets regulations. Project financing can be done through outside donations, government grants or be self-funded by the community. The designers can leverage direct expertise from Earthship Biotecture who can train locals to carry out the construction, or reach out to volunteers abroad and locally. However, too much help can present logistical challenges, requiring the designer to organize food, water and shelter for workers in advance.

4. **Think Future.**

   Up to this point, time, money and efforts have been poured into the project. The work does not stop post construction. Now that the earthship is built, the designer should think about project sustainability. This will require strong support from the community to maintain and repair the earthship when needed. By looking at the earthship's life-span, the designer can implement safety measures that will ensure that the project will carry out its purpose for years ahead.

5. **Expect the unexpected.**

   Every earthship will perform differently depending on the area of implementation. As Everson best puts it, research alone will not protect one from all unseen challenges. Therefore, the best way to prepare is to follow through with the project, but be open to change and surprises along the way.

This framework is meant to guide the designer in making an earthship for community development purposes. However, it should be noted that this process is not linear. Earthships are integrated systems requiring the designer to consistently consider how each design criteria affects one another.

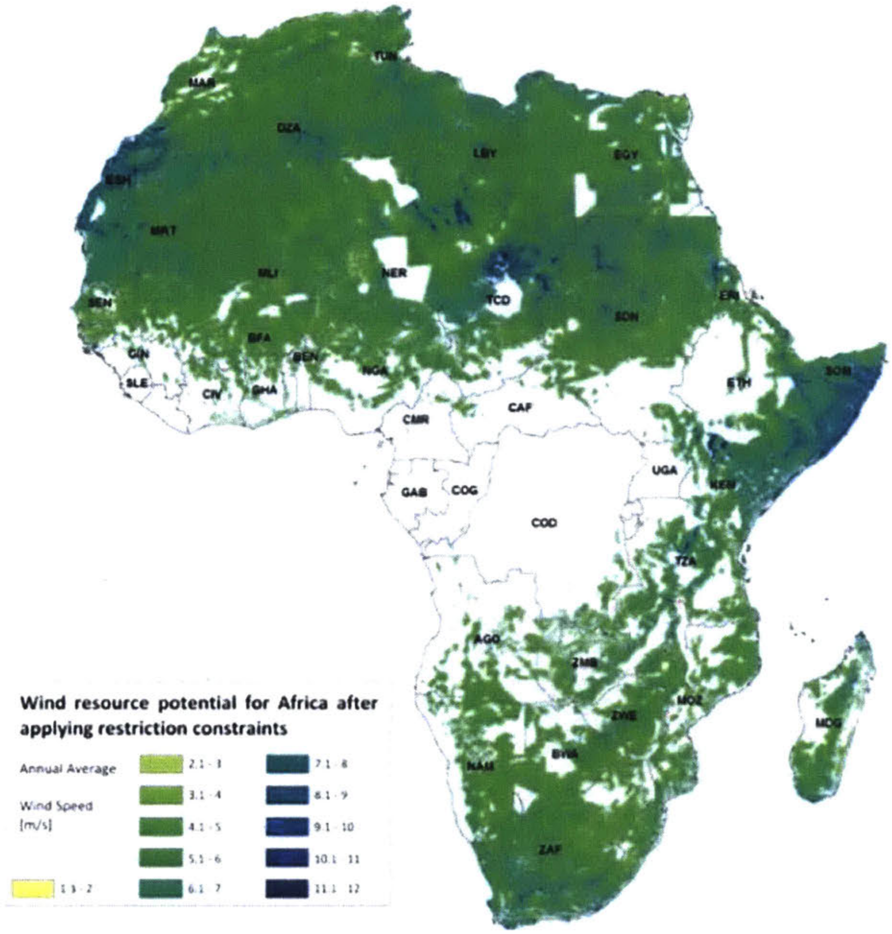
Chapter 5

Conclusion

In conclusion, earthships provide an alternative to current housing methods. In designing around fundamental human needs, earthships offer benefits that houses do not have today. The thermal regulation, energy, water collection, sewage, and food production systems provide residents with self-sufficiency that does not require reliance to large-scale regional utilities and authorities as well as long-term financial savings. This has attracted the attention of environmental enthusiasts around the world who want to turn trash into treasure as illustrated through the three earthship projects implemented in Africa. Each project offers a unique story and perspective in how earthships can be translated in the future to other parts of Africa.

The important design requirements and considerations have been outlined in this paper to help future designers list all potential factors that can impact project feasibility. Potential factors include location siting, identifying available materials and financial resources, subsystem design, government regulation awareness and cultural understanding. Each is vital in developing project success, but not all can be addressed at once. Every project will face different challenges especially in resource-constrained environments and therefore result in distinctive outcomes. Future projects will help to improve earthship design, but also help improve the quality of life for those involved.

Appendix



Appendix I: Wind energy potential in Africa. The northern, southern and most west tip of the continent have the fastest wind speeds, with highest being concentrated on the coasts (IRENA, 2014).

References

Delphi234. (2014). *English: Africa Precipitation Map*. Retrieved from https://commons.wikimedia.org/wiki/File:Africa_Precipitation_Map.svg

Earthship | Africa. (n.d.). Retrieved May 21, 2017, from http://earthship.com/grand-central/africa

Earthship | Grand Central. (n.d.). Retrieved May 22, 2017, from http://earthship.com/Grand-Central/?highlight=WyJyZWNvZ25pemVkIiwiZWFydGhzaGlwIiwiJ2VhcnRoc2hpcCci LCJlYXJ0aHNoaXAncyJd

Earthship | Organic Food Production. (n.d.). Retrieved May 23, 2017, from http://earthship.com/Systems/organic-food-production

Earthship Academic Research Overview, in Plain English. (n.d.). Retrieved May 22, 2017, from http://hackingtheearthship.blogspot.com/p/earthship-academic-research.html

Earthship Community Centre. (n.d.). Retrieved May 21, 2017, from http://empowerprojects.org/project/earthship/

Earthship Malawi - Kapita Community Centre. (n.d.). Retrieved May 21, 2017, from https://chuffed.org/project/earthship

Earthship Research: Earthship Europe. (2012). Retrieved May 25, 2017, from http://hackingtheearthship.blogspot.com/2014/12/earthship-europe_31.html

earthships. (2012, March 21). Africa Earthship Project Overview. Retrieved May 21, 2017, from http://earthship.com/blogs/2012/03/africa-earthship-project-overview/

earthships. (2013, September 4). 10 Reasons Why We Need An EarthShip Home. Retrieved May 21, 2017, from http://earthship.com/blogs/2013/09/10-reasons-why-we-need-an-earthship-home/

earthships. (2015, January 26). Earth Rammed Tire Walls. Retrieved May 23, 2017, from http://earthship.com/blogs/2015/01/earth-rammed-tire-walls/

Earthships in Africa. (n.d.). Retrieved May 21, 2017, from http://www.arcgis.com/home/item.html?id=e2748f79b3704da2864d76f7e40529a6

Eke, R. (2011). *Photo of Goodrich Waldorf School*.

Everson. (2009, March 13). Aardskip - Earthship: Soektog na ontwerp van 'n Aardskip / In search of an Earthship design. Retrieved May 21, 2017, from http://aardskip.blogspot.com/2009/03/soektog-na-ontwerp-van-n-aardskip.html

Everson, L. (2017, April 15). Aardskip Interview [Skype].

Goderich Waldorf School. (n.d.). Retrieved May 22, 2017, from http://www.goderichwaldorf.org/history.html

Hewitt, M., & Telfer, K. (2012). *Earthships in Europe* (Second edition). Bracknell: IHS BRE Press.

Hodge, O., Wexler, R., Open Eye Media (Firm), Independent Television Service, Sundance Channel, & Mongrel Media. (2008). *Garbage warrior*. Toronto: Mongrel Media.

IRENA. (2014). The Socio-economic Benefits of Solar and Wind Energy. Retrieved from http://www.indiaenvironmentportal.org.in/files/file/Socioeconomic_benefits_solar_wind.pdf

Kandoh, S., Clark, P., & Elliot, S. (2017, March 27). Goodrich Waldorf Earthship questions from an MIT student.

Kruis, N. J., & Heun, M. K. (2007). Analysis of the performance of earthship housing in various global climates. In *ASME 2007 Energy Sustainability Conference* (pp. 431–440). American Society of Mechanical Engineers. Retrieved from http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1603160

Reynolds, M. E. (1991). *Earthship*. Taos, N.M: Solar Survival Architecture.

Samarakoon, S., & Ntaukira, J. (2017, April 18). MIT Thesis: Kapita Community Center Earthship Questions.

Teddington. (1999). Sustainable Homes embodied energy in residential property development: A guide for registered social landlords.

Way Off The Grid: 6 Earthships That You Should Know. (2015). Retrieved May 21, 2017, from http://www.atlasobscura.com/articles/radically-ecological-earthships-from-around-the-world

WEO - Africa focus. (n.d.). Retrieved May 23, 2017, from http://www.worldenergyoutlook.org/resources/energydevelopment/africafocus/

WEO - Energy access database. (n.d.). Retrieved May 23, 2017, from http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/

WHO | Drinking-water. (n.d.). Retrieved May 23, 2017, from http://www.who.int/mediacentre/factsheets/fs391/en/

WHO | Key facts from JMP 2015 report. (n.d.). Retrieved May 23, 2017, from http://www.who.int/water_sanitation_health/monitoring/jmp-2015-key-facts/en/

World Health Organization (Ed.). (2011). *Guidelines for drinking-water quality* (4th ed). Geneva: World Health Organization.

Zeleza, P. T., & Codesria. (1997). *A modern economic history of Africa. Vol. 1, Vol. 1,*. Nairobi: East African Educational Publishers in association with the Council for the Development of Social Science Research in Africa.

Zifan, E., modified, and vectorized by Ali. (2016). *English: Africa map of Köppen climate classification.* Retrieved from https://commons.wikimedia.org/wiki/File:Africa_map_of_K%C3%B6ppen_climate_classification.svg