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Embodied Energy Assessment of Rainwater Harvesting Systems in Primary School Settings on La Peninsula Valiente, Comarca Ngöbe Bugle, Republic of Panama

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Environmental Engineering
Department of Civil & Environmental Engineering
College of Engineering
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ABSTRACT

The United Nations Millennium Development goals aim to make improvements in access to potable water. In the Bocas del Toro region of Panama, rainwater harvesting systems are making that goal more attainable. Rainwater harvesting, especially in rural, difficult access areas, may be a viable water source improvement that will allow a greater population to access improved water. This study uses the Carnegie Mellon University Economic Input-output Life Cycle Assessment tool to assess the embodied energy of plastic and ferrocement rainwater harvesting systems in rural Panama. Rainwater harvesting systems are assessed as source improvement technologies that increase access to potable water. This study adds to and compares its results to other source improvement LCAs that would potentially benefit developing communities in lesser developed countries.

1 INTRODUCTION AND MOTIVATION

The state of access to water in the Ngöbe populated regions of Panama is relatively poor compared to the more urbanized, non-indigenous regions of the country. The United Nations (UN) Millennium Development Goals measured no change in access to water in rural Panama between 2005 and 2008. Within this timeframe, of the rural Panamanian communities, 83% had access to improved water systems, with no improvement in this percentage within these dates (UN, 2011). Rural community data from the United Nations includes indigenous and non-indigenous populations, however, the World Bank reported that 43% of indigenous Panamanians do not have access to a close source of potable water (World Bank, 2000). As in many other parts of the world, government and locally built gravity flow water systems (i.e., aqueducts) in rural Panama are sometimes poorly constructed and maintained, and usually do not support entire communities with potable water (Suzuki, 2010). The need for improved water sources, provision of water, and access to easy collection is thus critical in the indigenous Comarca Ngöbe-Bugle region of Panama.

Rainwater harvesting is one of the most widely available source improvement technologies that is feasible and appropriate for this particular region and climate. For this study, the embodied energy of rainwater harvesting collection and storage is determined and compared to a similar assessment performed on four different source improvement systems in West Africa (Held, 2010). The embodied energy of a given intervention is the amount of energy harnessed within the intervention including direct energy to build and operate, and indirect energy in materials and services involved in the intervention. When considering the materials that comprise a technology, the embodied energy equals the quantity of energy that is consumed over its life cycle (i.e., materials production, manufacturing, or transportation). A Life Cycle Assessment, as defined by the Environmental Protection Agency, is a way of quantifying the environmental impact of, for example, a process, system, technology, or product. Environmental impacts can be assessed in terms of greenhouse gasses and energy. An economic activity is a tool that can be used for life cycle costing assessment (EPA, 2010).

The embodied energy assessment of rainwater harvesting systems (RWHS) in Panama is a new example of a source improvement assessment in a developing world setting that was previously not analyzed by Held (2010). Other important work in this area of study included that of Mo et al., (2010), Stokes et al., (2005), Lyons et al., (2009), Herz et al., (2002), and Matthews et al., (2008).

Held (2010) (and Held et al., 2011) determined and compared the embodied energy of four water source improvements and four point of use water treatment devices in a rural setting in Mali (West Africa). Using a Life Cycle Assessment (LCA) tool developed at Carnegie Mellon University (Carnegie Mellon University Green Design Institute, 2008), Held was able to measure the total embodied energy of each intervention, and compare their overall impact as an appropriate technology for the provision of potable water. He found that the solar pump intervention ranked the highest in terms of total embodied energy of the four source interventions studied, and the rope pump ranked the lowest. This showed that the rope pump consumed the least amount of energy (reported in Giga Joules per functional unit) over its assessment with 302 GJ consumed per solar pump versus 117 GJ consumed per rope pump (Held, 2010).

This report differs from the previous work of Held (2010), Stokes et al. (2005), Lyons et al., (2009), Herz et al., (2002), and Matthews et al. (2008), by focusing on populations in the Republic of Panama. The study locations were local community schools, composed of the same cultural indigenous group (the Ngöbe-Bugle), were of similar size, and were characterized as being comprised of a similar structure. The author's significant aspect of the research presented within this document determines the embodied energy for a source improvement technology that Held (2010) did not address – rainwater harvesting.

This thesis performs an embodied energy assessment of a school serving 100 students. The assessment also defines different water uses for a typical school day. This assessment aims to provide information to be able to make more accurate estimations into rainwater system sizing, demand and supply.

The embodied energy assessment portion of this thesis considers the resources consumed with establishing potable drinking water systems in school settings via rainwater harvesting. The embodied energy calculations can then be compared to the number of students attending each school that participated in this study (where a reference school of 100 students is determined). The end goal was to calculate in terms of cost and embodied energy, the broader environmental impact of provision of rainwater harvesting in rural Panama for students.

The significance of this research thesis is to analyze the cost in terms of energy of rainwater harvesting in primary schools as a viable source of potable water in rural

Panama, by the method of Economic Input Output-Life Cycle Assessment (EIO-LCA). The objective of this thesis is to determine the embodied energy harnessed in rainwater harvesting systems, made of plastic and ferrocement, based on daily water use at the rural school level. The main question this thesis asks is: What is the embodied energy per capita (based on water use per student) of Panamanian manufactured plastic and locally manufactured ferrocement rainwater harvesting systems in school settings in rural Panama?

The report will quantify the overall embodied energy of rainwater harvesting systems in rural Panama. The motivation behind this report was to create a Panamanian based standard of embodied energy (per student capita) in order to assess communities for future rainwater harvesting projects. The information that will be determined will be useful for policy makers who are concerned about the embodied energy of development projects. The author was also motivated to study this to understand the energy impact her rainwater harvesting Peace Corps project has over its lifetime. The results from this thesis could potentially be applied to other communities, estimating the total embodied energy of improving water accessibly with rainwater harvesting. The communities have been lacking proper potable water coverage, but the rainwater harvesting option is feasible based on the climate, economics, and the ability to provide water access. Transportation is the limiting factor to rainwater harvesting installations in this specific, water access only location.

One motivating factor supporting and encouraging rainwater tank use in the area of La Peninsula Valiente is the large amount of rainfall present each year. Graph 1.1 provides the average rainfall per month in the Bocas region which can range between 83.8 and 563.6 mm per month (World Weather Information Service, 2011).

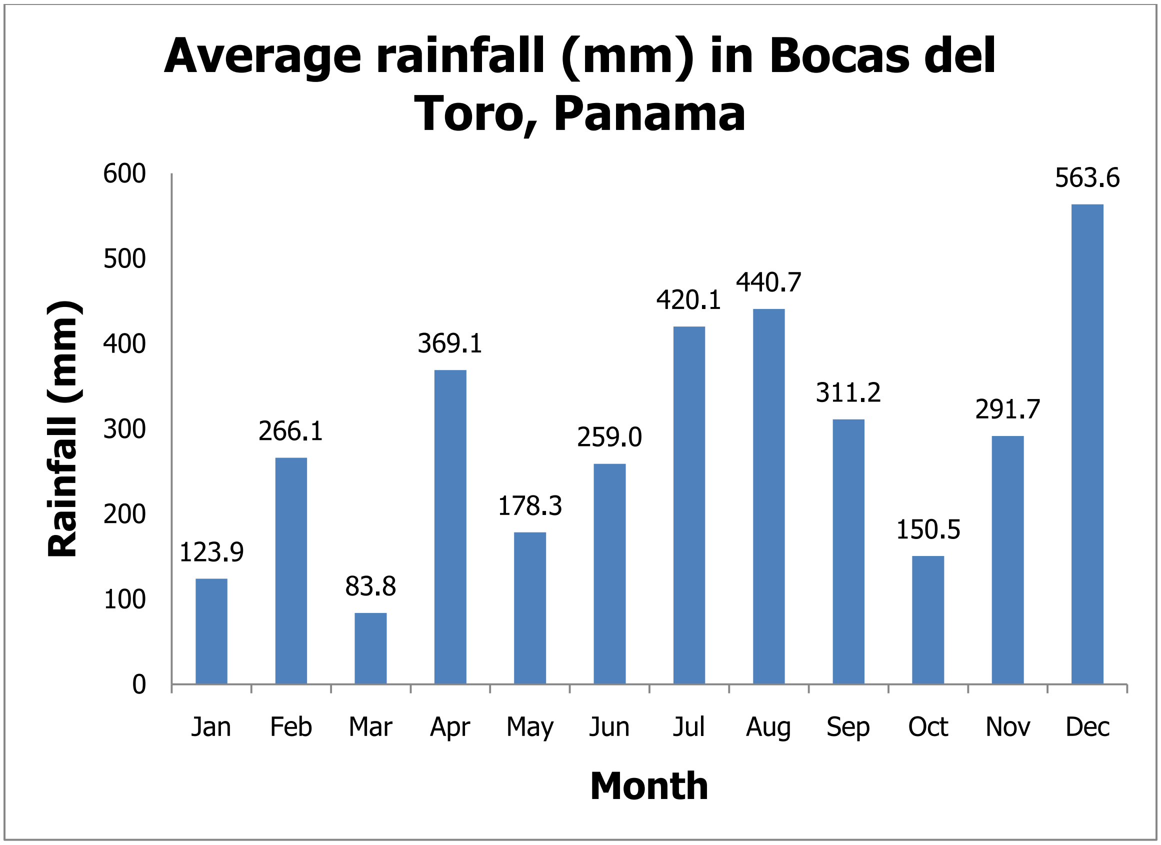

Figure 1: The Mean Total Rainfall for the Bocas del Toro Region of the Republic of Panama. (Graph produced by author based on data obtained from World Meteorological Organization website: http://www.worldweather.org, 25 April 2011).

Figure 1 shows the mean total rainfall in the Bocas del Toro Region of Panama. It should be noted that March is the month of lowest rainfall, and the rainfall data used within this study to signify the minimum amount of water available. A table of this data is located in Appendix A.

The engineering project that provided the raw data for this research should improve access to potable water in the area of the Bocas del Toro side of the Comarca Ngöbe-Bugle region of Panama. Prior to the installment of the rainwater harvesting systems, women in the community would walk to a stream or unprotected aqueduct line to fetch water for the schools. The addition of the rainwater harvesting tanks to the community schools should alleviate some of this burden of collecting water as well as provide a daily source of cleaner water to the school students.

This study uses rural, coastal, subsistence farming communities in the Republic of Panama as the setting in which water quality interventions were constructed, applied, and implemented. The author has lived and worked for two years in Punta Sirain, one of the communities that participated with this study. She volunteered as a Water & Sanitation Engineer working on water infrastructure, sanitation, and water treatment for 29 months, as part of her Peace Corps service. Her living conditions in Panama allowed her to directly experience the intervention of rainwater harvesting, while time spent in the communities influenced the feasibility of the project and the community's motivation towards obtaining their goal of in-school potable water.

2 LITERATURE REVIEW

2.1 Assessment of Panama's Water Supply Interventions

In 2010, Ryu Suzuki conducted research throughout Panama analyzing and assessing the condition of Waterlines (an American based Non-Government Organization who regularly funds aqueduct projects in rural Panama) and Peace Corps Volunteer (PCV) built gravity fed water supply systems (referred to as aqueducts). He selected 27 communities, 19 of those being identified as rural indigenous Ngöbe communities, similar to this thesis's context of study. He developed a rating system to assess the conditions of the existing aqueducts to evaluate what their standing conditions were and to assess if they were running correctly. A description of the aqueducts distribution system can be found in Appendix C. As part of his research, Suzuki found that only 48.1% of the systems were functioning in the acceptable category (rating 4 and 5 out of a 1-5 scale) in terms of the distribution system. This implies that only about half of the aqueduct systems evaluated were functioning properly (Suzuki, 2010).

This finding could be interpreted that there is a lack of water security even when aqueduct systems are implemented. In these cases of failed aqueducts, rural communities may lack reliable potable water, suggesting there may be a need for less complex and more decentralized improved water systems. Rainwater harvesting may be a viable option in such situations due to the frequent amount of rainfall in the Bocas del Toro region. Suzuki's study shows that there is a need for improved water systems to provide in-home potable water. Only about half of the systems within Suzuki's study were providing adequate water in their distribution system. Of the roughly 50% of cases that were not receiving adequate water from their aqueducts, it can be inferred that they could possibly benefit from rainwater harvesting because there is adequate rain fall along with failed aqueduct infrastructure.

2.2 Life Cycle Assessment and Application to Embodied Energy Calculations

2.2.1 Overview of Life Cycle Assessment

The Environmental Protection Agency (2010) defines an LCA as:

A technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:

- Compiling an inventory of relevant energy and material inputs and environmental releases;
- Evaluating the potential environmental impacts associated with identified inputs and releases; and,
- Interpreting the results to help make a more informed decision.

This process can be used to assess and compare different processes to make informed future decisions regarding engineered systems and technology. It also can show linkages and relationships between processes, products, or services. LCA studies are becoming a popular form of study and research, especially for their application to make suggestions for future technological advancements. LCA studies have been performed on a wide range of systems, from water systems, to manufacturing processes, to comparing multiple-use versus one-time-use products. LCA assessment can also identify the area of a process that consumes the most resources, and can identify those parts that need the most conservation focus. More specifically, an Economic Input-Output LCA (EIO-LCA), as used within this research, evaluates use of aggregated economic sector level data, which is a measure of how much environmental impact can be attributed to each sector of the economy and how much each sector purchases from other sectors (Hendrickson, 2010).

2.2.2 The Carnegie Mellon EIO-LCA

The Carnegie Mellon's Green Design Institute's Economic Input-Output Life Cycle Assessment (CMU EIO-LCA) tool was used in this research to evaluate the embodied energy of rainwater harvesting collection and storage systems. A complete description on how the tool was used is provided in Chapter 4, Methodology. This tool was developed to simplify and allow access to estimating materials, energy resources, environmental emissions and economic activities (Carnegie Mellon, 2011). A complete description of the tool can be found on the Carnegie Mellon EIO-LCA website: www.eiolca.net. The results produced from this tool could help to guide future development decisions that involve rainwater harvesting. This research follows the methods developed by Held (2010). Within his assessment, Held used the Carnegie Mellon EIO-LCA. Therefore, to accurately compare the results from this study and his, the same tool is used.

2.2.3 Application of LCA Tools Towards Determining Embodied Energy of Water Supply & Treatment Within the United States

Water systems have a significant impact on energy consumption and use on a global scale. Developed countries that utilized large water purification and treatment plants consume energy in their provision of water. Additionally, the production of energy is heavily water consuming. Providing access to potable drinking water almost always come at a price- in dollar amounts for cost per unit volume water, or in terms of energy. Using the Carnegie Mellon LCA tool, this present study aims to quantify the embodied energy footprint that rainwater harvesting systems carry. The RWHS examples assessed within this paper come from Panama, and are made out of ferrocement and plastic. Just as water in the United States has an energy price, this study aims to discover the embodied energy of these systems using an LCA.

Developed water systems, made from steel and other metal piping systems that can span miles attribute to the embodied energy of the entire infrastructure system. Herz (2002) found that the materials used to build the system, in comparison to materials used for buildings, can attribute to a significant portion of energy consumption. Herz (2002) compared the materials used in a water infrastructure system, including pipes and sewers, to the development mass of buildings. Just as Herz (2002) assessed the system from a materials standpoint, this study quantifies its energy impact based on the EIO-LCA of the different materials in each given rainwater harvesting system. LCAs are able to assess all aspects of water provision, including transportation and delivery of water. This usually large portion of the embodied energy of a developed world system is typically less in a developing world context. The developing setting is generally more localized, and therefore less energy intensive. The Input-Output LCA model is able to generate embodied energy data based on a specific economy that assesses the embodied energy of all aspects of the system- construction, operation, transportation, and maintenance. This form of LCA is generally more accurate than user-based direct material and energy input tools, because they are bias to how the user inputs data. An EIO-LCA is generally more accurate since it uses the specific economy of the country and sector of goods to operate its calculations.

An LCA has been applied to a variety of systems to assess their energy consumption which is part of environmental impacts. Some of these studies, specifically in the field of potable water systems, include: A Water Treatment Facility in Kalamazoo Michigan (Mo et al., 2010), Alternative Water Supply Systems (Stokes et al., 2005), The Importance of Carbon Footprint Estimation Boundaries (Matthews et al., 2008) and The LCA of Drinking and Wastewater Treatment Systems of Bologna City: Final Results (Tarantini et al., 2001). Additionally, The Life Cycle Assessment of Water Mains and Sewers (Herz et al., 2002), and The Life Cycle Assessment of Three Water Supply Systems: Importation, Reclamation and Desalination (Lyons et al., 2009) add to the growing research of how water and energy are interrelated. However within this thesis the Carnegie Mellon University EIO-LCA will be applied in the rural Panamanian context, which has not been analyzed before.

The work of Mo et al. (2010) provides an LCA of a water distribution system within the context of the United States. This report highlights the usefulness of LCAs and the importance of understanding LCAs in making future predictions about pricing and carbon footprints. Mo et al.'s work was based on the Kalamazoo, Michigan public water supply system. The Kalamazoo study differs from this study's research because it is a public supply system within a developed world setting. This thesis is based on water use solely within a developing world context. Its assessment considers the cost of energy necessary to provide the service of drinking water from the Kalamazoo public water supply including operation, maintenance, construction, materials and labor, which is similar to this application and Held's (2010). Mo et al. concluded that over a 100 year lifetime, the Kalamazoo water supply system is estimated to consume 259 tera joules per year (one time construction = 1219 TJ, operation & maintenance = 247 TJ/year).

The work of Stokes and Horvath (2005) provides an LCA of alternative water supply systems within the context of the United States as well. Stokes and Horvath assessed different types of alternative water sources. These alternative sources included recycling water, water reuse, and water importation. Stokes and Horvath performed their assessment with an EIO-LCA: the total embodied energy consumption as well as the resources consumed by maintenance procedures. Their most significant findings were that the energy and air emissions caused by the infrastructure of alternative water systems were significant when compared to the relative cost of the water supplied. Stokes and Horvath also found that when recycling water in Northern and Southern California there was a difference in energy demand, highlighting the fact that the location and context of water use affects the LCA and resource consumption.

The work of Matthews et al. (2008) assesses the carbon footprint of estimation boundaries with CMU's EIO-LCA. Their work was targeted to teach the reader about the manufacturing process of automobiles in comparison with the carbon emissions produced by driving a car. They sought to identify the true source of carbon emissions, whether the greater impact is caused by consumers or corporation and suppliers, so that mitigation can be targeted and applied most cost effectively. They used a "hybrid analysis" model approach which combines basic input-output LCA models with impact data for specific goods, services, and organizations (Matthews et al., 2008). This is a common practice with LCA analyses since it includes process level data and economic parameters. But the author notes that limits and boundaries must be established and that coherent rules covering the extent of that business and its end users can affect the supply chain and, therefore, multiple possibilities and tradeoffs must be considered when determining boundaries and rules. Although this study was performed on automobiles, and not a water system, the same LCA tool and concepts were used for a hybrid method of LCA assessment.

The work of Lyons et al. (2009) highlights the concept that for future generations it is important to rely on local water availability, and reduce the carbon footprint of transporting water over large distances. Bottled water could be an example of water that comes with a high energy cost due to manufacturing and transportation, and localized in-home rainwater harvesting may be viewed as minimally energy intensive. Lyons et al. considered the differences in water importation, reclamation, and desalination to compare what form of obtaining improved water was the most energy intense, using a life cycle assessment. He found that seawater desalination was the most energy intensive and that plant operations within this technology were much greater than the initial construction phase. Water reclamation proved to be the technology with the minimal impact.

LCAs are an excellent way of interpreting the energy footprint associated with a technology. As population increases in the future, and water becomes more scare, it will be important to understand how to obtain the most amount of water using the last amount of energy. Performing an LCA of the economic input-out method, as these studies and the present study do, give an economic justification, depending on the sector of embodied energy. This information may enable future policy makers to make informed decisions about water provision and energy distribution.

2.2.4 Application of LCA Tools Towards Determining Embodied Energy of Water Supply & Treatment Outside of the United States

An LCA was performed in the city of Bologna (Italy) on the city's drinking and wastewater treatment systems. The Bologna study is significant and relevant to this research because it assessed the LCA and environmental impacts of the current wastewater treatment and drinking water facilities as part of an initiative to assess water consumption reduction, rainwater harvesting, and grey water reuse. The study compared the "existing" system to the "innovative" system to assess whether a 50% reduction of water use would be achieved by the implementation of appropriate water reducing devices and technologies. The Bologna study incorporates rainwater harvesting, which this research focuses on, but differs from this research since it is set in an urban context. This example points out that to further improve the environmental performances of the "existing" water system, it is necessary to reduce the energy consumption, optimizing design and operation of pumping devices (Tarantini & Ferri, 2001). The study at hand does not make additions to the urban research, but does a similar study between plastic and ferrocement rainwater harvesting interventions within a rural setting.

Held (2010) completed a similar master's thesis based on the EIO-LCA assessment of source protection and point of use improvements in rural Mali, Africa. His methodology is described in Chapter 4, Methodology, as it closely resembles that of this study. His results demonstrated the energy demand and LCAs of four point of use improvements and four source improvements. This research is different because its context varies from Held's, being located in Panama versus Mali. He compared a solar pump, India Mark II, improved well, rope pump, and four point of use treatments which included boiling, a ceramic filter, a biosand filter and chlorination. He found that the solar pump embodied the most energy at 302 Giga joules (GJ) and the rope pump embodied the least amount of embodied energy at 117 GJ. These two technologies had the highest and lowest embodied energy results, from the eight interventions assessed. Held did not analyze rainwater harvesting, which allows this research to be considered as an addition to his study (2010).

The technologies that Held (2010) assessed were composed of a human energy portion that contributed to the total embodied energy. It was critical to include this portion of the embodied energy in his study since by the nature of the technology human energy was necessary in order to obtain the improved water. For example, the rope pump had a large human embodied energy associated with it since energy exerted by a human was necessary to operate the pump which would bring water to the surface for collection. The rainwater harvesting systems within this study do not include a human energy component because no human energy is required to access the water. For this study, the portion of Held's (2010) study that encompassed human energy was neglected in order to compare the two studies on a material-only bases.

3 OBJECTIVES AND HYPOTHESIS

The overall objective of this study is to demonstrate a means of assessment of the embodied energy impacts of water quality interventions, specifically rainwater harvesting, as they could be applied to implementation in the 270,000 (population) rural Bocas and Comarca dwelling Ngöbe-Bugle Panamanians, half of them currently without access to a functioning improved water source. Additionally this study aims to assess and understand the embodied energy of rainwater harvesting systems in comparison to other source improvement technologies in developing world settings.

3.1 Specific Objectives of This Study

- Analyze the effectiveness of rainwater harvesting in school settings as a viable source of potable water in rural Panama.
- Determine the embodied energy present in these rainwater harvesting systems based on daily water demand at the school level.
- Compare the normalized embodied energy of Panamanian manufactured plastic and ferrocement storage tanks used in rainwater harvesting systems, and to source improvements based in Mali, West Africa.

4 METHODS

4.1 Geographical and Cultural Setting

La Peninsula Valiente is located on the North Western Caribbean side of Panama, part of the Comarca Ngöbe-Bugle Province. This indigenous protected land lies east of the Bocas del Toro archipelago and is home to roughly five thousand inhabitants. The Ngöbe Bugle people traditionally occupy this land. They are one of the five indigenous groups in Panama. In the 1990s the area was established as its own province by the Panamanian government to protect the land, homes and livelihoods of this indigenous group. Because of this, La Peninsula Valiente is almost 100% Ngöbe, with a small amount of Latino and Afro-Antillean influence from the Bocas region. Access to this area is limited to boat transportation from the port town of Chiriquí Grande that leaves and returns once daily.

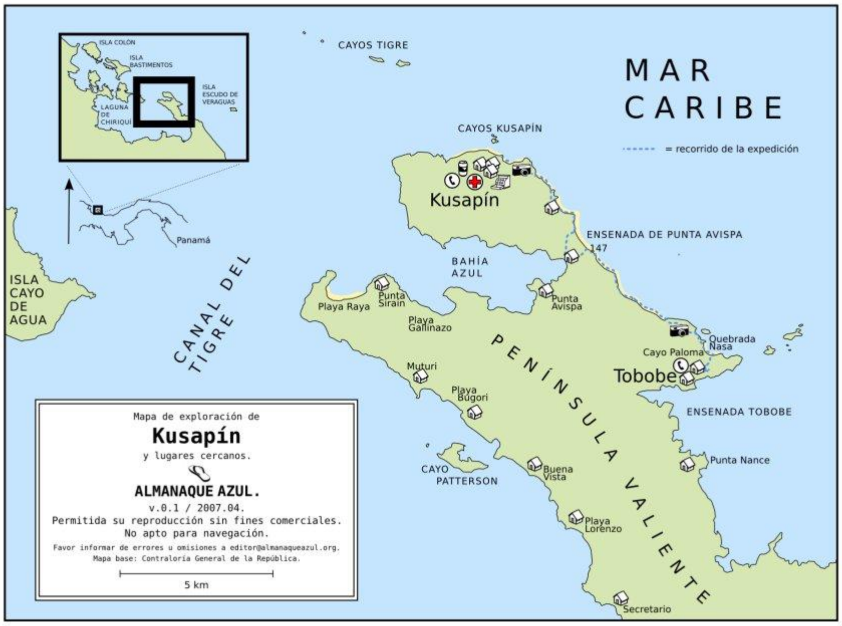

Figure 2: La Peninsula Valiente: The Brave Peninsula, Comarca Ngöbe-Bugle, Panama. The communities that participated in this study were located on the inside mouth of the peninsula, laying on Bahia Azul. (http://www.almanaqueazul.org/peninsula-valiente/). Permission to use granted May 10, 2011 website correspondent: (Puedes usar el mapa sin problema.)

Currently, the area has very little infrastructure, lacking improved sanitation systems or protected water systems. The water systems that do exist are generally uncovered or untreated, do not reach the entire population of the communities they serve, dry up, or are not maintained properly. It has been observed by the author that the water supply is unreliable and unsafe to drink without treatment. The most common and traditional method of obtaining water is by collecting water close to the home from a small creek, seep, or spring. These sources are not treated nor protected, and from the author's observation little in-home water treatment was regularly being performed prior to drinking. Water is generally collected in the morning by the women of the households to use for drinking, cooking, washing, and cleaning. It is typically stored in five gallon buckets (usually uncovered) in the kitchen area of the house for use throughout the day. When water buckets are left uncovered the water is susceptible to contamination by insects, animals, and children that can easily access the water.

Water designated for use at the schools (within the specific location of this research) was primarily obtained from gravity fed water supply systems (referred to as "aqueducts" in this thesis), which are generally not protected at the source nor treated at the point of use (for more information on how these systems are designed, see Mihelcic, et al., (2009)). Collecting water is a part of the school's daily functioning routine, especially for the women who work as cooks of the schools' lunches. It has been observed by the author that the use of aqueducts is mainly for convenience instead of health, since it is general knowledge that the water is not treated from the aqueduct source. Within most communities in the area lies a basic aqueduct system that might have been built by the Panamanian government during the past twenty years, with the intention of safely serving the community members. For example, in Punta Sirain (one of the communities included in this study) lies an open tank that holds groundwater flowing from a seep point. This location is roughly ten feet higher in elevation that the central part of the community, within which lies the school. Due to the fact that this tank has no cement cover and no proper filtration, the water running through the PVC tubing system is not protected nor treated. The people of Punta Sirain have a basic understanding that this water is not ideal, however it is used at the school since it is conveniently located in the back of the building and there is no other source (protected or unprotected) close by. This unimproved situation was part of the motivation to install a rainwater harvesting system located at the school's kitchen, where water is most frequently used. After assessing the school's water needs, the project that this research stems from, aimed to place a rainwater harvesting system with an access tap directly into the kitchen of the community school. The school location was applied to the other three participating communities. This would provide access to cleaner water more directly, and with less chance of contamination.

4.1.1 The Need for Improved Potable Water Systems

When water is collected without applying protective precautions as a method of collection, contamination through transportation occurs. It is especially dangerous when the person transporting the water does not regularly wash their hands, especially after defecation. Even if the water is being collected from an improved source, the possibility of water contamination is increased if the collector is required to travel a distance with the collected water. The chances of contamination increase as the distance from the source increases (Wright et al., 2004).

Rainwater harvesting interventions, as in the scenarios described in this study, may reduce these methods of pathogen transmission and contamination since the rainwater source provides potable water directly into the homes of its consumer. This decreases the transportation element of possible contamination and can potentially reduce diseases (Wright et al., 2004). The motivation to install rainwater harvesting systems was to provide access to rainwater, and therefore cleaner water, with a tap directly into the kitchens of the schools for easy and more sanitary use.

In rural Panama, access to water in indigenous communities is often limited to collecting water from nearby streams and creeks. In more developed villages, government-built aqueducts are present, but due to lack of maintenance of the systems, may not function safely or efficiently (Suzuki, 2010). Rainwater harvesting is a source improvement that has been experiencing an increased acceptance in the area of Bocas del Toro due to the relative lower cost of materials in comparison to a gravity fed aqueduct systems. The abundance of rainwater in the area also identifies this technology as a very logical and appropriate choice for provision of potable water.

Personal home rainwater harvesting systems are becoming popular since families are able to purchase and maintain their own system. Purchasing their own system is a means of securing their water, and removing their dependence on aqueducts that can become unreliable, and untreated sources that can cause sickness. One problem seen often in community-wide aqueduct settings is the lack of responsibility individuals feel toward water conservation and maintenance. Unless a functioning team or committee exists, community members and aqueduct patrons may not feel compelled to assist in the upkeep of the system, since their home is a small portion of the larger aqueduct system (Suzuki, 2010). Personal rainwater harvesting tanks remove this aspect of neglect by the broader community because they force each family to be responsible for their own system, and therefore their own potable water supply. This is called self supply water accessibility (Rosenfeld, 2009). A family who has invested in their own self supply system might increase their ability to correctly maintain it, and therefore have more consistent access to potable water (Rosenfeld, 2009).

4.1.2 Geographical Barriers to Development

La Peninsula Valiente is an area of Panama that is susceptible to relatively slower development than similar communities, due to its geographical location. Cost of boat transportation to the area is an influential barrier that hinders all aspects of development, in comparison to similar mainland communities that have access to a paved road. Access to a road may signify access to markets, consumerism, and jobs, in a greater volume than in an area that can only be accessed by boats. A road can potentially allow people greater movement than a water-only access area.

The remoteness of this region was a main factor in the motivation behind this research project. Transportation is an expensive aspect of development projects on La Peninsula Valiente. Lighter materials, such as plastic rainwater storage units (tanks), are less expensive to transport than heavier materials such as cement that would be required to build an aqueduct. The weight of materials is an added cost in terms of fuel, since all materials must be transported by boat to reach this region. In general, aqueducts are more culturally accepted than rainwater harvesting systems due to the local perception that an aqueduct tends to signify that the benefitting community is now an established community.

The communities required more education on the benefits of rainwater versus an aqueduct since culturally an aqueduct has been a more desired and accepted technology as a method of obtaining potable water. A feasibility study was performed by the author during her stay in the community of Punta Sirain to establish a level of interest in proceeding with a rainwater harvesting system project. The feasibility study concluded that the community members were indeed interested in the rainwater technology and plans were made to move forward with the project. A description of how this study was performed in a group setting is located in Appendix D.

The plastic rainwater tanks have a lifetime of roughly ten years, based on the AMANCO brand manufacturer's guarantee, manufactured in Panama. After ten years the plastic may wear down, become brittle, easily break, or develop leaks. This area of Panama is also susceptible to intense sunlight due to its coastal location and proximity to the equator, which may speed up the decay process. This study assumes that the plastic rainwater harvesting systems will be active for ten years. Additionally this study assumes that the zinc roof will last at least 50 years (Kraft et al., 2003), based on the longevity of the zinc material and strength.

4.2 Defining the Functional Unit

In this study, the functional unit represents a rainwater harvesting system that is able to capture and store water for 100 students at eight liters per student per day, which represents the water demand of a school of 100 students. In comparison, Held (2010) defined his functional unit as 12 cubic meters (12,000 L) of water per day, which is enough water to serve a rural Mali village of 600 inhabitants, within a ten year time frame. Within one school for this study, the functional unit represents a water demand of 800 L/day, based on the author's observation of each student requiring 8 L/day for hand washing, drinking, and use in the kitchen for lunch preparation and cleanup (on a ten year timeframe based on the tank's lifetime). The parameters of this specific water demand were defined by the daily water needs as described in Table 1.

Table 1: Daily water demand in three different situations: survival demand, medium demand, and the author's observation demand, for water needs that students require on a daily level, based on liters per student per day (Reed, 2005)

	Survival	Medium	Author Observation
Water Use	L/student/day	L/student/day	L/student/day
Drinking	3.5	3.5	1
Food preparation & cleanup	2.5	2.5	5
Personal hygiene (hand washing)	-	6.5	2
TOTAL	6	12.5	8

The survival demand is the water necessary for human survival, when water is limited. The Medium demand is a reasonable quantity of water for human use, when water is more available than the survival demand. The author observed student using 8 liter of water per day. This demand falls within the range of survival and medium water demand, which makes it an appropriate value for primary school students- where water is somewhat limited and water for other domestic uses such as bathing is not taken into account. In terms of one month, the functional unit equates to a water demand of 24,000 L/month, to suffice 100 students.

The minimum mean rainfall is 83.8 mm which typically falls in the month of March (World Weather Information Service, 2011). Typically March is the month with the least amount of rainfall. The system was designed at this minimum to ensure water throughout all months of the year. March was also chosen because students attend class starting in the month of March. One millimeter of rainfall is equal to 1 L/m^2 of rainfall; a conversion used to calculate rainfall for a given surface area.

The minimum daily rainfall with which this study assumes equals:

$$\frac{83.8\,\frac{L}{m^2}}{30\;days} = 2.8\,\frac{L\,/m^2}{day}$$

The minimum daily rainfall of 2.8 L/m^2/day is then applied to the number of days in an average month; this study assumes 30 days in an average month. It should be noted that students do not attend school all 30 days. However, using 30 days builds in a safety factor into the collection design. It was also considered by the author based on the fact that she observed the teachers and other community members using the water collected by the rainwater harvesting system on non-school days for other purposes.

The surface area of one standard zinc panel used as roofing is 3.253 m^2. By multiplying the surface area of one panel of zinc by the minimum daily rainfall this study calculates that in one day one panel of zinc is able to collect 9.1 liters of water.

$$\frac{2.8\,L\,/m^2}{d} \times 3.253\,\frac{m^2}{panel} = 9.1\,\frac{L\,/panel}{d}$$

A runoff coefficient is applied to this value to represent water loss from leaks in the collection system. The coefficient can also account for water loss due to the roof pitch. At 80% water recovery, this study shows that one panel of zinc is able to collect 7.3 liters of water per day (7.3 L/panel/day). The slight overlap of two panels on the roof itself was disregarded.

The school requires 800 liters per day to support the water demand of 100 students. One zinc panel is able to collect 7.3 L/day at 80% recovery; therefore by dividing the demand by the panel capacity this study enables the design of a collection roof area.

The number of panels needed to accurately support the water demand is:

$$\frac{800\,\frac{L}{day}}{7.3\,\frac{L}{panel}/day} \approx 110\,panels$$

in order to supply 100 students with adequate potable water.

The width of one zinc panel is standard at 3.5 feet, and there are two sides to a typical school roof in Panama, therefore, the length of the school can be calculated. 110 panels divided by two sides of a school yields 55 panels. 55 panels multiplied by 3.5 feet (the width of one panel) yields 192.6 ft (approximately 60 meters). This factor can be adjusted based on number of students. A table summarizing the functional unit used in this study are located Appendix B.

4.3 Input-Output Assessment and Embodied Energy

The methodology for the input-output embodied energy assessment for source improvements such as rainwater harvesting followed the methodology used by Held (2010). Held based part of his calculations on the Carnegie Mellon EIO-LCA model, to calculate embodied energy of different source improving technologies as this study does.

The selection process to choose the most appropriate model is based on the economic status of the Republic of Panama as well as the author's knowledge of in-country manufacturing. The plastic materials that were used to construct the rainwater harvesting systems were all manufactured in Panama. However, an LCA model that assesses the embodied energy of a given process or product does not exist for the Republic of Panama. The next best logical choice was to use the LCA tool from Carnegie Mellon University with the assumption that the Chinese model is most appropriate for this situation because the manufacturing and economic status of Panama more closely resembles that of China (versus the other available models for U.S., Germany, Canada, or Spain).

The input-output assessment tool is a means of determining the structure of an economic activity. An economic activity input can be used to estimate the economic output of a given activity. The tool is able to calculate an output from the economic value of the material being assessed, depending on where it is manufactured. I/O tools can produce an output that is measured in energy, or using environmental stressor indicators, such as greenhouse gases. When the output is determined, the user can then assess the activity in terms of its overall impact, either in energy consumed throughout its lifecycle or its environmental footprint. This study focuses on embodied energy output as a means of evaluating the process of installing rainwater harvesting systems in rural Panama.

The Carnegie Mellon EIO-LCA tool encompasses a method that is based on $\mathbf{n \times n}$ matrices. This was used to model an economy with $\boldsymbol{n}$ sectors to form matrix $\mathbf{A}$. The element $\mathbf{a}_{ij}$ represents the amount of economic input from the sector $\boldsymbol{i}$, which would be required to produce one dollar of output from that given sector, $\boldsymbol{j}$**.** The symbol $\mathbf{y}$ represents the vector that represents the demand for goods by sector. Therefore $\mathbf{y}_i$ is the demand from sector $\mathbf{i}$. $\mathbf{x}_{direct}$ is the output of the economy which is labeled $\mathbf{(I+A)y}$.

The sum of the outputs is represented by the series **$(I + A + AA + AAA + \ldots)$**. The Leontief inverse matrix, given by **$(I-A)^{-1}$,** is also equivalent to this series. This is often called the total requirements matrix.

A challenge that exists by using LCAs to evaluate process within lesser developed countries is using an appropriate model that accurately calculates an output based on the economy of that country. The problem arises when data and model matrices do not exist for many lesser developed countries, such as Panama. When no such matrix exists, a similar model must be assumed. This study approaches this challenge by assuming that Panama is a lesser developed country similar to China, one of the models available with the CMU EIO-LCA.

Additions to the model are being updated constantly; therefore it should be noted that this study used the Chinese 2002 tool accessed in April of 2011. Import data from Panama (International Trade Centre, 2011) were used to determine which matrix was most appropriate for each commodity.

The Republic of Panama uses US dollars; therefore, all of the original costs of materials recorded in Panama are equivalent to US dollars. The CMU EIO-LCA encompasses five country LCA matrix models, one being a Chinese economic model. This tool operates in 2002 Chinese Yuan thus conversions were necessary. Information from the International Monetary Fund was used to convert 2010 U.S. dollars to 2002 Chinese Yuan. This rate equates ¥8.277 Chinese Yuan equal to one U.S. dollar (International Monetary Fund, 2011). Table 2 provides the list of materials, and their respective cost for input into the CMU EIO-LCA.

Table 2: Cost of one complete functional unit (including two different systems) of materials converted into Chinese Yuan from the 2002 conversion value

Item in RWH System	Cost per one functional unit worth of material	Cost Converted $1.00 = ¥8.277 (2002)
	[US Dollars]	[Chinese Yuan]
Plastic tank	$350.00	￥2,896.95
PVC piping	$300.00	￥2,483.10
PVC elbow	$10.00	￥82.77
Zinc	$1,650.00	￥13,657.05
Ferrocement	$123.20	￥1,019.73
Wire & screen	$81.90	￥677.89

The material cost in Chinese Yuan is the value used for input into the LCA modeler. It should be noted that this table accounts for all materials for one RWHS functional unit of two systems (plastic and ferrocement). For example, the price of zinc in this table represents the cost of zinc that will provide a roof large enough to provide 800 L/day (110 zinc panels).

4.4 Rainwater Harvesting System Materials

The rainwater harvesting systems assessed within this study are both the same size but constructed with two different types of materials- ferrocement and plastic. The roof collection size was the same for both systems as they both provide water for 100 students at a rate of eight liters per student per day. Therefore the roof size required to meet the functional unit is composed of 110 zinc panels, as previously determined. The PVC plastic collection piping materials were also the same quantity for both the ferrocement storage unit case and the plastic storage unit case. The amount of PVC piping needed is 400 feet of PVC piping and two 4” PVC elbows.

4.4.1 Plastic System Intervention

The plastic rainwater harvesting system is composed of the materials to serve 100 school children as defined in the functional unit. The plastic water storage tank is shown in Figure 3.

Figure 3: A Rainwater Harvesting System Made of the Plastic Tank Option

The plastic system utilizes a Panamanian manufactured tank that is able to store 2,100 liters of water. This tank cost roughly $350.00; converted to 2002 Chinese Yuan equals ¥2,900.00.

4.4.2 Ferrocement System Intervention

The ferrocement system is composed of the same sized tank as the plastic system, but constructed using cement, metal wire and screen. It is based on the ferrocement tank design criteria determined by Watt (1978). The materials cost roughly $200.00 (2002 Chinese Yuan: ¥1,750.00). Table 3 shows the material design break down of the ferrocement storage tank to support 2,100 liters of water. Table 4 shows the difference in material cost between the two cases of storage tanks, excluding the roof collection portion of the system which is identical for both cases. Gravel and sand can be found (usually free of charge) in construction sites in this study and therefore do not need to be calculated as are the cement and metal products. The specific CMU EIO-LCA economic sectors with which these materials were categorized and were used to calculate the embodied energy are provided in Table 5.

Table 3: The cost of materials of a ferrocement tank designed to hold 2,100 L of water

	Quantity needed for 15000 L	unit	material	Quantity needed for 2100 L tank	unit	Cost/unit		Cost/material need for 2100 L design	
Walls:	2300	kg	**cement**	**322**	kg	$ 10.00	/per 50 kg bag	**$**	**64.40**
	5	m^3	**sand**	**0.7**	m^3	$ -	in site	**$**	**-**
	1200	m	**4 mm wire**	**168**	m	$ 1.00	/ lb	**$**	**33.60**
	345	ft	**screen at 1m wd**	**48.3**	ft	$ 1.00	/ ft	**$**	**48.30**
Floor:	2100	kg	**cement**	**294**	kg	$ 10.00	/per 50 kg bag	**$**	**58.80**
	5	m^3	**sand**	**0.7**	m^3	$ -	in site	**$**	**-**
	2.5	m^3	**gravel**	**0.35**	m^3	$ -	in site	**$**	**-**
	(Watt 1978)						Metal total	$	81.90
							Cement total	$	123.20

The cost of materials for the different types of tanks were calculated and added to find the total cost of the two types of rainwater harvesting systems. The materials break down is provided in Appendix E.

Table 4: Difference in cost, in Chinese Yuan (2002), of the different materials involved in the two tanks cases assessed in this study

ELEMENT	MATERIAL	PLASTIC SYSTEM CASE	FERROCEMENT SYSTEM CASE
TANK	Plastic	¥ 2,900.00	¥ -
	Cement	¥ -	¥ 1,050.00
	Metal	¥ -	¥ 700.00
TOTAL		¥ 2,900.00	¥ 1,750.00

Table 5: The material application of the industry and economic sectors of the CMU EIO-LCA used within this study

Material	Industry Sector	Economic Sector	Economic Sector Number
Manufactured tank	Rubber, Plastic, and Mineral Products	Plastic products	48
PVC piping	Rubber, Plastic, and Mineral Products	Plastic products	48
PVC elbow	Rubber, Plastic, and Mineral Products	Plastic products	48
Cement	Rubber, Plastic, and Mineral Products	Cement, and cement asbestos Products	49
Wire	Iron, Steel, and Metal Products	Metal Products	60
Screen	Iron, Steel, and Metal Products	Metal Products	60
Zinc Roof	Iron, Steel and Metal Products	Metal Products	60

Table 5 shows the different economic sectors that this study utilized specifically for the CMU EIO-LCA Chinese tool. The economic sectors are displayed in Table 5 to provide a reference if a similar study was to be performed. The Chinese model has a limited selection of sectors compared to the U.S. model; however these sectors are sufficient for this study.

The plastic rainwater harvesting system is composed of $660.00 of plastic materials (tank and piping) and $1,650.00 of metals (zinc panels) for the roof. The ferrocement RWHS is composed of $120.00 of cement, $80.00 in wire and screen metal materials, $1,650.00 of metal material (zinc panels) for the roof, and $310.00 of piping materials. To accurately compare these two material types, the amount of material included for the ferrocement tank is sufficient to construct a tank that is the same size as the manufactured plastic tanks (2,100 L).

The economic value that was inputted into the LCA tool for each economic sector was 1 million Yuan, and output is provided in tera joules (TJ). Once the embodied energy was determined, the value was converted to kilojoules (kJ) and then normalized based on the fraction of the real cost of the materials.

For example, $350 of plastic material (tank) equals ¥2,898 in 2002. This value was rounded up to ¥2,900. I million Yuan was applied to the tool; the calculated results (4.57 TJ) can be found in Appendix F Table F.3. The value (1 million Yuan applied to the Plastic sector) was converted into kilojoules (kJ), and then corrected to the true cost of materials by multiplying by this fraction: (¥2,900/¥1,000,000). The resulting value is 11,882,000 kJ (11.88 GJ).

5 RESULTS AND DISCUSSION

The following section provides the embodied energy results for the two types of rainwater harvesting systems (plastic and ferrocement) and a normalized comparison with the results from Held's (2010) study. Results were calculated based on a school's water system designed to capture and store enough water for 100 students using the month of lowest rainfall (March) as referenced earlier in this study.

5.1 Embodied Energy Results

In compliance of the methodology of this study, the results from the CMU EIO-LCA are as follows: Table 6 shows the total cost of the two types of rainwater harvesting systems, listed by element, material type, and converted as described in Chapter 4-Methods.

Table 6: Total cost, by material, of the elements that compose a rainwater harvesting system (shown in 2002 Chinese Yuan)

ELEMENT	MATERIAL	PLASTIC SYSTEM	FERROCEMENT SYSTEM
Roof	Metal	￥ 13,700.00	￥ 13,700.00
Piping	Plastic	￥ 2,600.00	￥ 2,600.00
Storage tank	Plastic	￥ 2,900.00	￥ -
Storage tank	Cement	￥ -	￥ 1,050.00
Storage tank	Metal	￥ -	￥ 700.00
	Total Cost (¥):	￥ 19,200.00	￥ 18,050.00

Table 7 shows the total embodied energy of each element, in kJ and GJ. Table 6 and 7 indicate that the plastic and ferrocement systems have similar embodied energies – 88.29 GJ for the plastic system versus 87.18 GJ for the ferrocement system, when both collection and storage elements are considered. When normalized to a volume of 1000 liters, as most data is for water based LCA studies, the result is 110.36 GJ and 108.98 GJ respectively, for the plastic and ferrocement systems. These values are measures of the total embodied energy of the entire system based on the 2002 Chinese economic matrix of the CMU EIO-LCA.

Table 7: Total embodied energy, by material, for the elements that make up a rainwater harvesting system with plastic and ferrocement storage tanks (shown in kJ and GJ), including the collection and storage elements of the system

ELEMENT	MATERIAL	PLASTIC SYSTEM	FERROCEMENT SYSTEM	UNIT
Roof	Metal	63,157,000	63,157,000	kJ
Piping	Plastic	11,882,000	11,882,000	kJ
Tank	Plastic	13,253,000	0	kJ
Tank	Cement	0	8,914,500	kJ
Tank	Metal	0	3,227,000	kJ
Total Embodied Energy:		88,292,000	87,180,500	kJ
Total Embodied Energy:		88.29	87.18	GJ
Total Embodied Energy normalized to 1000 L:		110.36	108.98	GJ

Table 8 shows that approximately 85% of the total embodied energy is embodied in the roof and piping portion of the system. The collection portion of the two systems is identical, consisting of roof paneling and PVC piping as described in the functional unit section. The storage tank is the remaining portion of the system which consists of different types of materials. It encompasses approximately 15% of the total embodied energy, differing by only 1.1% between the two systems. Since about 85% of the rainwater harvesting system is composed of the collection element, a more accurate approach to compare the embodied energy of the two systems is only of the storage portion of the system.

Table 8: The percentage of the embodied energy, for each of the two material types, which account for the collection portion and storage portion on the entire rainwater harvesting system

		PLASTIC SYSTEM	FERROCEMENT SYSTEM
COLLECTION	ROOF & PIPING % of SYSTEM	85.0%	86.1%
STORAGE	TANK % of SYSTEM	15.0%	13.9%

The Panamanian government has built school systems in small towns and villages throughout Panama using uniform materials and a uniform design. In this context, the roofs of the schools were not built solely for the collection of rainwater, but for protection against rain and other elements. This alters the life cycle assessment of the system. Rainwater collection is the roof's secondary purpose, whereas the storage tanks sole purpose is rainwater storage. Because the roof's main purpose is for protection, and because it is uniform across the different schools in design and materials, it is disregarded in this portion of the study. When the collection portion is disregarded, only the tanks are compared. For this study the ferrocement tank is a mixture of metal screen, metal wire, and cement, and the plastic tank is a single manufactured plastic tank. For this study they are assessed at the same volume of 2100 liters, however two conversions were performed. The first conversion accounts for a water demand of 800 liters per day and the second conversion accounts for a tank size of 2100 liters.

Table 9 shows the total embodied energy for the plastic and ferrocement systems, considering only the collection portion of the system. This number does not include the roof or collection piping. The collection portion of the system was disregarded since the school's roof was built for protection, not rainwater collection. The results, 16.57 GJ and 15.18 GJ, represent the embodied energy of the storage portion for 1000 liters of water- the normalized volume typically used in water based LCAs, and converted from the functional unit of 800 liters of water demand per day. The second results, 7.88 GJ and 7.21 GJ, represents the embodied energy normalization results (to 1000 L), converted from the actual size of the tank (2100 L). These normalized values allow for a comparison to Held's previous study in the next section of this report.

Table 9: Embodied energy of the storage portion (tanks) of plastic and ferrocement rainwater harvesting systems

ELEMENT	MATERIAL	PLASTIC SYSTEM	FERROCEMENT SYSTEM	UNIT
Tank	Plastic	13,253,000	0	kJ
Tank	Cement	0	8,914,500	kJ
Tank	Metal	0	3,227,000	kJ
Total Embodied Energy:		13,253,000	12,141,500	kJ
Total Embodied Energy:		13.25	12.14	GJ
Total Embodied Energy normalized to 1000 L from 800 L:		16.55	15.18	GJ
Total Embodied Energy normalized to 1000 L from 2100 L:		7.88	7.21	GJ

Held (2010) determined the embodied energy of four source protection interventions. He concluded that of the source interventions assessed, the intervention with the highest embodied energy was the Solar Pump at 302 GJ. The lowest intervention's embodied energy was the rope pump at 117 GJ (per 12000 liters /600 people).

The functional unit used in Held's (2010) study and the functional unit used in this study were normalized to accurately compare the two sets of results. This was performed by adjusting the given results to represent 1000 liters of water, so that both different sets of data could be assessed on the same scale. Previous literature on water based LCAs, as discussion in Chapter 2, also were assessed based on a standard water volume. A summary of Held's (2010) and this study's functional unit are provided in Table 10.

Table 10: Functional Unit as determined and used by Held (2010) and within this study

Functional Unit of Source Intervention	Water Provided	# People Served	Lifetime of Intervention
Study Author	[L]	[#]	[# years]
Held	12000	600	10
Green	800	100	10

Table 10 shows the differences in functional units between Held's (2010) study, and this study. The main comparisons that should be noted is that Held's study was based on a water demand volume of 12,000 liters per day and this study was based on a water demand of 800 liters per day. These results from the functional unit base were both adjusted to represent 1000 liters of water per day.

Held's (2010) study included embodied energy results that are strongly correlated with the human energy component of the source interventions. This study's source improvements- rainwater harvesting systems – are not comprised of a human energy component. This is because after the one time assembly of the system, there is no human labor that is associated with access to the water provided. This differs from, for example, the improved well which Held assessed, because in order to access the water, human energy is exerted to pull the water up from the well. To accurately compare the embodied energy of the source improvements of this study to Held's, the human energy portion was not considered. Therefore, the analysis was that of Held's material-only results and this study's, which is material-only by nature. This step is critical in the comparison portion of this study to produce meaningful conclusions. Table 11 displays the total embodied energy, the embodied energy of the materials, and the materials normalized for the source improvements Held assessed.

Table 11: Embodied energies of four source improvements that Held (2010) assessed, converted to terms appropriate to compare with this study's results

Source Protection Intervention Unit: Embodied Energy [GJ] / 600 people / 10 years	Total (including human energy)	Material (without human energy)	Material; normalized to 1000 L
Solar Pump	302	181.77	15.15
India Mark II	245	137.26	11.44
Improved Well	134	3.05	0.25
Rope Pump	117	6.28	0.52

Table 11 provides Held's (2010) results in terms that can be compared to this study. It should be noted that the material embodied energy does not have a direct relationship with the total embodied energy since each source improvement consists of a different percentage of material versus human energy. The final result column is directly relative to this study because it is Held's results in terms that can be compared to this study's: Embodied energy [GJ]/1000 L water/10 years. People served, which is included in the functional unit, may be neglected at this point since the study compares a specific volume of water, regardless of how many people that quantity can serve. Table 12 compares these normalized results to this study's normalized embodied energy results for rainwater harvesting systems.

Table 12: A comparison of the embodied energy of four source improvements from the study Held (2010) conducted and the two results from the rainwater harvesting systems of this study (embodied energy [GJ]/1000 L/10 years)

Author	Source Protection Intervention	Material Embodied Energy [GJ] / 1000 L /10 years
Held	Solar Pump	15.15
Held	India Mark II	11.44
Held	Improved Well	0.25
Held	Rope Pump	0.52
Green	RWHS Plastic	16.55
Green	RWHS Ferrocement	15.15

Table 12 shows, when compared on normalized terms the rainwater harvesting tanks consume a similar amount of energy as the Solar Pump. The India Mark II is also comparable, falling slightly lower than the first three, with the Improved Well and the

Rope Pump being very low in embodied energy. This could be attributed to the fact that the Improved Well and Rope Pump have very low impact materials while the other technologies have a higher energy consumption embodied in their materials. Held's (2010) un-normalized results show that the Rope Pump consumes about a third of the energy that the Solar Pump does. A graph of the provided results may be seen in Figure 4.

Figure 4 shows the comparison between the four source improvement that Held (2010) assessed, and the two source improvements that this study assesses. The plastic rainwater harvesting system is shown to be the most energy consuming in providing 1000 liters of water, over a life span of ten years.

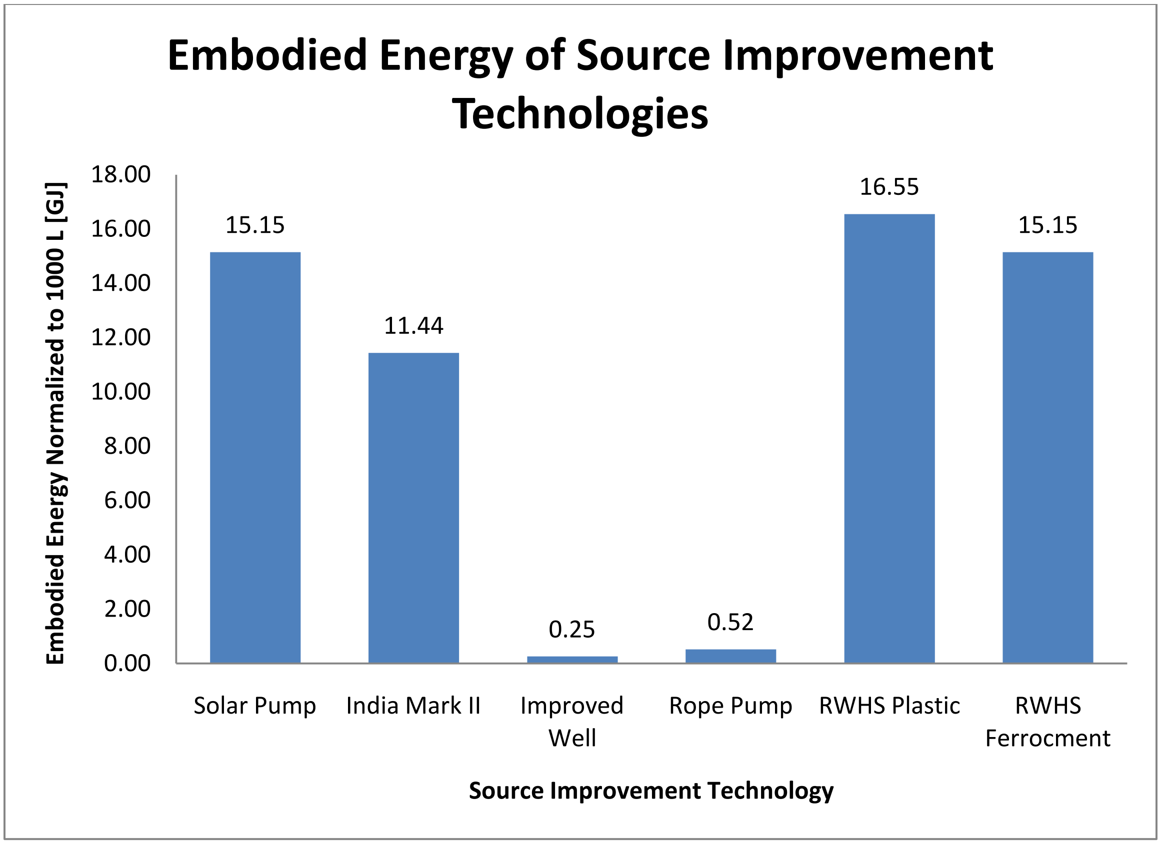

Figure 4: A Comparison of the Embodied Energy of Six Source Improvement Technologies, Based on a Water Demand of 800 Liters per Day, Normalized to 1000 Liters

Another normalization consideration for the rainwater harvesting systems is adjusting the volume of water from 2100 liters to 1000 liters. The previous calculation was converted from a functional unit of 800 liters- the water demand of a school of 100 students per day. However, the actual size of the manufactured tank is 2100 liters. Therefore, another approach to the normalization is to convert the embodied energy to 1000 liters by using the conversion factor of (1000/2100). This would give an embodied energy result in terms of the entire tank, not just on the portion of the tank needed to provide the daily demand of 800 liters. The following table shows the embodied energy of the source improvements when this methodology was applied.

Table 13 produces results that differ from the first comparison of Held (2010) and this study. Using the methodology based on a 2100 liter tank, the embodied energy basically halved compared to the methodology of assessing the embodied energy based on a student water demand of 800 liters. The graphical representation of these results can be seen in Figure 5.

Table 13: A comparison of the embodied energy of four source improvements from the study Held (2010) conducted and the two results from the rainwater harvesting systems of this study (embodied energy [GJ]/1000 L/10 years), using the conversion factor based on a 2100 liter tank

Source Protection Intervention	Material Embodied Energy [GJ] / 600 people / 10 years; normalized to 1000 L
Solar Pump	15.15
India Mark II	11.44
Improved Well	0.25
Rope Pump	0.52
RWHS Plastic	7.88
RWHS Ferrocement	7.21

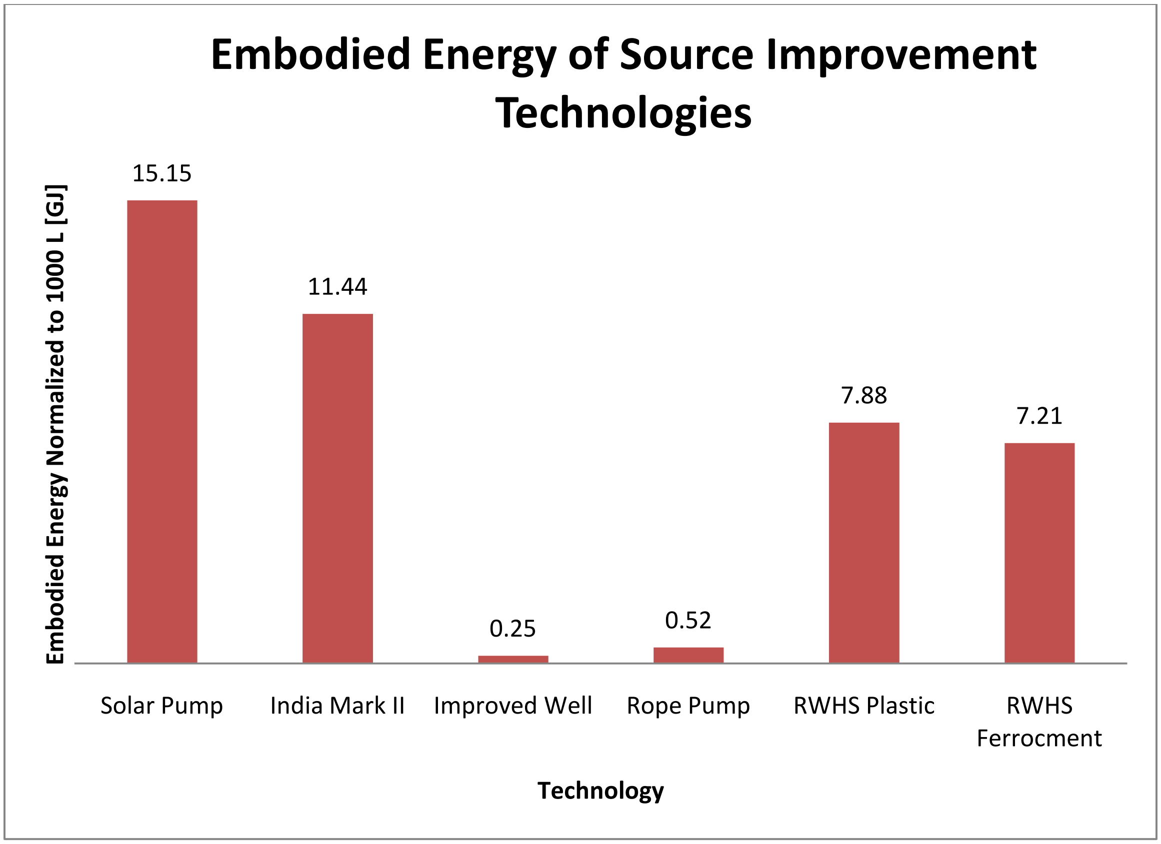

Figure 5: A Comparison of the Embodied Energy of Six Source Improvement Technologies, Based on a Water Demand of 2100 Liters per Day, Normalized to 1000 Liters

Figure 5 compares the source improvements of Held's (2010) study and that of this study, based on a normalization factor of rainwater harvesting tanks sized 2100 liters. This comparison places the rainwater harvesting systems in between that of Held's (2010) study. Since this comparison is based on a tank of 2100 liters and not a water demand, the embodied energy is spread over a greater quantity, lessening it compared to the method of calculating based on daily water demand. These technologies' embodied energies range in between the improvements that Held assessed.

5.2 Discussion

This study determined that there is a very small difference in embodied energy between plastic and ferrocement rainwater harvesting systems, in rural Panama. Since the embodied energy is very similar for both systems, consumers might base their choice on a variety of other considerations including transportation cost, practicality of transportation methods, and availability of materials. Although this information is somewhat beyond the scope of the consumer, decision makers can use this information when assessing future rainwater harvesting system project proposals in the area of Bocas del Toro.

To successfully choose which system is more appropriate for a specific location or community, other considerations should be noted. Excluding the roof and piping, the ferrocement option is approximately $150 cheaper than the plastic tank ($350 for one plastic tank versus $120 worth of cement and $80 worth of metal wire and screen). The difference of $150 could be considered an economic advantage of choosing the ferrocement over the plastic material type.

The location of a given community can also affect which type of material is chosen. The amount of cement necessary for a 2,100 L tank is heavier to transport to a community than a lighter plastic tank. In rural Panama, hiking or boat transportation is sometimes necessary to reach a community. Although plastic is lighter, it occupies more space than cement, which is heavy but compact to transport. Depending on the rural location, the closest available market to purchase plastic tanks may be too far away. Thus, communities that are located a great distance from a central city or market, such as the communities assessed within this study, may be too far away to buy plastic tanks at a cost that would be affordable to the consumer. Especially for locations very far from a capital area that have access to markets and goods, cement may be a much more appropriate option. Cement can be found available in lesser developed areas more commonly than manufactured plastic tanks can be found. In some cases, plastic may be culturally preferred but ferrocement may be more feasible and available.

Tank material may also influence water quality in a storage tank. Schafer (2010) studied the impact of three different types of storage tank materials, on water quality in Cochabamba (Bolivia). Her study comprised of testing the water quality of water that was stored in polyethylene, fiber glass, and fiber cement tanks. Her results for the fiber cement (similar to ferrocement) and polyethylene (a type of plastic commonly used to manufacture rainwater harvesting tanks) can be compared to this study since those materials were also used in this study. Schafer (2010) concluded that *E. coli* was present in higher concentrations in the polyethylene tanks than in the fiberglass or the fiber cement tanks. This most likely occurs because the black plastic tanks become hotter than the cement tanks in the sunlight, making them able to breed more bacteria in the hot conditions. Schafer also noted that the water temperature inside the elevated storage tanks is above the threshold level of 15°C cited by other studies as causing increased microbial growth (Fransolet et al., 1985; Donlan and Pipes, 1988; Smith et al., 1989; Donlan et al., 1994 – From LeChevallier et al., 1996).

> "One implication of the warm water temperatures found in all elevated storage tanks, but especially in the black polyethylene tank is that there is the potential for increased bacterial growth" (Schafer, page 76).

Schafer found that 33.3% of the samples taken from polyethylene tanks resulted in *E. coli* concentrations that were higher than the Bolivian water quality standards. Also, 55.4% of samples taken from fiber cement tanks exceeded the same water quality standard. The better choice for rainwater harvesting system implementation in developing world settings may thus be ferrocement tanks, because of their apparent lower concentration of bacterial growth. Tank cleaning frequency, the location of the tank with respect to sunlight, and climate are also contributing factors to link bacteria growth to cultural norms and landscape.

The material based embodied energy assessment that this study examined and then compared with that of Held (2010), assesses source improvement technologies that may be used in developing world settings to improve access to potable water. This comparison between the two studies shows that based on a water volume of 1000 liters, the source improvements technologies range from 0.5 GJ to about 16 GJ. Depending on the conversion factors used (either total size of the tank or daily water demand) of the rainwater harvesting systems, the rainwater harvesting system fall extremely similar to the Solar Pump and India Mark II, or fall in the range of these two technologies and the Improved Well and Rope Pump-which resulted in an embodied energy more than 16 times less than the Solar Pump (the highest result).

Held (2010) used a different set on economic matrices for his study, than solely the Chinese model that was used within this study. Although the methodology is the same, the different matrices may produce results that are not completely accurate to directly compare. This should be noted when considering the comparison results for this study. Although the results shown here appear to be meaningful in comparison to Held's (2010), the difference in economic matrix may account for an error that cannot be mimicked within this study. Policy makers using this data for developmental source improvement decisions should consider this data, as well as local information, climate norms, feasibility and cost of the materials in the location that they are working.

6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

This study concludes that:

- Rainwater harvesting systems are a viable method to provide sufficient water to schools in the Bocas del Toro region of Panama, based on the regional climate and average rainfall
- The embodied energy of plastic and ferrocement water storage tanks for a functional unit of the capacity to collect and store 800 L/water/day were determined to be very similar (88.28 GJ for the plastic system versus 87.18 GJ for ferrocement system); and other considerations such as local availability, transportation feasibility, provision of water quality, and cultural acceptance should be taken into consideration when selecting a system
- The collection portion of a rainwater harvesting system (zinc roof panels and PCV piping) make up approximately 85% of the total embodied energy of a rainwater harvesting system, for both plastic and ferrocement cases
- When normalized to account for a water volume of 1000 liters, the rainwater harvesting systems prove to be comparable to the four source interventions that Held (2010) assessed with a similar LCA study

There is a need for more accurate LCA tools and models that focus on the economic sectors of Latin America. Future research in LCAs of Central America might be more accurate if Latin American LCA tools were developed.

Further research should also include rainwater harvesting life cycle assessments based in the United States, Africa, South America or Asia.

An anthropological study might include an assessment of local perceptions of domestic rainwater use, or, a study of perceived differences between using ferrocement versus plastic storage tanks for domestic water storage. Another beneficial study of rainwater harvesting technology could include how the aesthetics of the tanks, or material choice, may affect the user acceptance of the tank.

Water quality is another aspect of rainwater harvesting that was not looked at closely within this study. Future work could more closely compare and contrast the water quality differences between ferrocement and plastic rainwater harvesting systems.

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APPENDICES

Appendix A: The Mean Temperature, Total Rainfall, and Number of Rain Days for the Bocas del Toro Region of the Republic of Panama

Month	Mean Temperature °F		Mean Total Rainfall (mm)	Mean Number of Rain Days
	Daily Minimum	Daily Maximum		
Jan	68.7	87.4	123.9	16.6
Feb	68.4	87.3	266.1	14.6
Mar	68.9	87.8	83.8	14.8
Apr	70.5	88.5	369.1	15.2
May	72.0	89.4	178.3	16.7
Jun	72.0	89.6	259	17.9
Jul	71.1	88.7	420.1	20.9
Aug	71.2	89.2	440.7	18.4
Sep	71.6	89.4	311.2	15.8
Oct	71.6	89.1	150.5	16.4
Nov	71.2	88.9	291.7	17.0
Dec	69.1	87.8	563.6	20.0

(Obtained from World Meteorological Organization website: http://www.worldweather.org, 25 April 2011)

Appendix B: Summary of the Functional Unit Used in This Study

1 functional unit:	A rainwater system to capture and store water for 100 students at 8 L/student/day	
Serves:	100	students
Water demand per student:	8	L/student/day
Total Water demand per day:	800	L/day
Minimum RW fall (March):	83.8	$L/m^2/month$
Days per month:	30	day/month
Surface Area of 1 zinc panel:	3.253	m^2
Width of 1 zinc panel:	3.5	ft
	PER DAY	
Water Demand:	800	L
Minimum RW fall (March):	2.8	L/m^2
1 zinc panel provides:	9.1	L
@ 80 % collection:	7.3	L
# of panels needed for collection:	110	panels
Panels per roof side:	55	panels
Length of side of roof:	192.6	ft
	58.7	m
Roof Length for one school:	60	m

Appendix C: Suzuki's Methodology for Rating Aqueducts in Rural Panama

Distribution systems within Suzuki's study were rated 1-5 based on the following criteria.

Score	Score Description
1	No taps, no valves, major inequity of water pressure and flow, very exposed and leaky tubes
2	Leaky or broken taps, no valves, some inequity of water pressure and flow, exposed and leaky tubes
3	Some leaky or broken taps, control valves, some inequity of water pressure and flow, exposed tubes, minimum leaks
4	Adequate pressure and flow at all houses, control valves, very little leaky or broken taps, tubes buried, minimum leaks
5	Adequate pressure and flow at all houses. Physical infrastructure is intact including; tap stands, service line control valve, main line control valves, tubes are buried.

Appendix D: Peace Corps POCA Feasibility Assessment for Community Based Decision Making

The community members of Punta Sirain participated in a feasibility study based on the methodology of the POCA system, developed by the U.S. Peace Corps. This method, allows participants to list and weight the pathway options of achieving a goal. Usually three options are listed as possible methods of achieving the overall goal. The community members then list of pros and cons that are associated with the three options on the table for the participants to see. Participants fill out the following table to visually see the positive and negative aspects of each option of fulfilling their goal. Once the activity is complete, the members vote on an option based on the positive and negative aspects that they agreed upon.

GOAL:		
Option 1:	Option 2:	Option 3:
Pros: + + +	Pros: + + +	Pros: + + +
Cons: - - -	Cons: - - -	Cons: - - -

Appendix E: Materials Break Down for Ferrocement Tank

The cost of materials of a ferrocement tank designed to hold 2,100 L of water. Gravel and sand can be found in construction sites and therefore do not need to be calculated as the cement and metal products in the EIO-LCA tool.

	Quantity needed for 15000 L	unit	material	Quantity needed for 2100 L tank	unit	Cost/unit		Cost/material need for 2100 L design
Walls:	2300	kg	**cement**	**322**	kg	$ 10.00	/per 50 kg bag	**$ 64.40**
	5	m^3	**sand**	**0.7**	m3	$ -	in site	**$ -**
	1200	m	**4 mm wire**	**168**	m	$ 1.00	/ lb	**$ 33.60**
	345	ft	**screen at 1m wd**	**48.3**	ft	$ 1.00	/ ft	**$ 48.30**
Floor:	2100	kg	**cement**	**294**	kg	$ 10.00	/per 50 kg bag	**$ 58.80**
	5	m3	**sand**	**0.7**	m3	$ -	in site	**$ -**
	2.5	m3	**gravel**	**0.35**	m3	$ -	in site	**$ -**
							Metal total	$ 81.90
							Cement total	$ 123.20

Appendix F: The Top Ten Sector Results for an LCA of Cement, Plastic, and Metal

Table F.1: Sector results for cement

Sector	**CEMENT**	Tot Energy TJ	Coal Coke TJ	Petroleum TJ	Nat Gas TJ	Non-Foss Elec TJ	Other Energy TJ
	Total for all sectors	*8.49*	*6.94*	*1.22*	*0.11*	*0.205*	*0.014*
49	Cement and cement asbestos products	3.9	3.2	0.563	0.024	0.113	0
85	Electricity and steam production and supply	3.27	3.07	0.147	0.02	0.02	0.014
7	Coal mining and processing	0.134	0.114	0.011	0	0.01	0
8	Crude petroleum products and Natural gas products	0.105	0.004	0.062	0.035	0.004	0
93	Water freight and passengers transport	0.094	0.007	0.086	0	0	0
56	Steel-processing	0.088	0.072	0.009	0	0.006	0
36	Petroleum refining	0.073	0.019	0.047	0.005	0.003	0
32	Paper and products	0.07	0.058	0.007	0	0.005	0
91	Highway freight and passengers transport	0.069	0.005	0.063	0	0	0
53	Other non-metallic mineral products	0.062	0.051	0.009	0	0.002	0

Appendix F (Continued)

Table F.2: Sector results for metal

Sector	**METAL**	Tot Energy TJ	Coal Coke TJ	Petroleum TJ	NatGas TJ	Non-Foss Elec TJ	Other Energy TJ
	Total for all sectors	*4.61*	*3.61*	*0.731*	*0.088*	*0.165*	*0.011*
85	Electricity and steam production and supply	2.63	2.47	0.118	0.016	0.016	0.011
56	Steel-processing	0.376	0.311	0.039	0.002	0.024	0
60	Metal products	0.274	0.16	0.069	0.006	0.039	0
55	Steel-smelting	0.128	0.106	0.013	0	0.008	0
8	Crude petroleum products and Natural gas products	0.101	0.004	0.06	0.034	0.004	0
54	Iron-smelting	0.08	0.066	0.008	0	0.005	0
93	Water freight and passengers transport	0.071	0.005	0.065	0	0	0
91	Highway freight and passengers transport	0.07	0.005	0.064	0	0	0
58	Nonferrous metal smelting	0.069	0.041	0.013	0	0.015	0
36	Petroleum refining	0.066	0.017	0.042	0.004	0.002	0

Appendix F (Continued)

Table F.3: Sector results for plastic

Sector	**PLASTIC**	Tot Energy TJ	Coal Coke TJ	Petroleum TJ	NatGas TJ	Non-Foss Elec TJ	Other Energy TJ
	Total for all sectors	*4.57*	*3.34*	*0.838*	*0.228*	*0.152*	*0.011*
85	Electricity and steam production and supply	2.53	2.37	0.114	0.016	0.015	0.011
42	Synthetic chemicals	0.457	0.303	0.066	0.057	0.032	0
8	Crude petroleum products and Natural gas products	0.262	0.01	0.156	0.088	0.009	0
38	Raw chemical materials	0.231	0.153	0.033	0.029	0.016	0
36	Petroleum refining	0.162	0.043	0.103	0.01	0.006	0
43	Chemicals for special usages	0.131	0.086	0.019	0.016	0.009	0
48	Plastic products	0.124	0.045	0.053	0	0.026	0
91	Highway freight and passengers transport	0.066	0.005	0.06	0	0	0
93	Water freight and passengers transport	0.062	0.005	0.056	0	0	0
7	Coal mining and processing	0.053	0.045	0.004	0	0.004	0