An energy, water and disease disaster management module: A techno-economic feasibility analysis

BY

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THESIS

submitted for the fulfillment of the degree of

MASTER OF SCIENCE (PHARMACY)

AUGUST 2016

ABSTRACT

Intermittent energy and water supply are current challenges faced by many residents in South Africa. South Africa is one of the more water scarce countries in the world; this coupled with the lack of infrastructure makes it challenging to provide every citizen with their right to basic water and sanitation. With millennium development goal 7C not being addressed in many areas, residents experience sub-standard living conditions, which drastically increases the vulnerability of marginalised groups to epidemics. In the sustainable development goals improving sanitation and drinking water has been identified as one of the most effective and least expensive means of reducing fatalities and increasing public health. There is a need for a mobile laboratory that demonstrates power and water self-sufficiency, which is capable of on-site diagnosis and water treatment. The unit will have the ability to perform independent compliance monitoring of municipal water supply, treat inadequate water and provide surplus electricity to surrounding areas. A literature-based study was performed utilizing several scientific databases to identify current methods of power and water production in previous disaster management and humanitarian relief situations. Based on findings three example laboratories were theoretically designed; structural modelling, systems simulation and optimization and sensitivity analyses were performed with HOMER Pro, PackVol and SketchUp. A cost benefit analysis was performed with the social return on investment methodology. Novel human waste processing was performed with fly ash and simulated faeces. Bacterial species identification in ice samples was performed with the API 20E protocol and limited equipment as a proof of concept for field deployment. A hybrid system consisting of PV panels, a wind turbine and biomass generator showed promise for displaced humanitarian relief camps; with every 1 ZAR capital invested resulting in 3.13 ZAR social benefit. A system consisting of PV panels and a battery bank proved to have the least environmental impact and the grid supply laboratory showed a cheaper cost of energy alternative for needs provision. Fly ash showed potential as in nutrient recovery and as a fertility aid to soil. The units developed function as a means to increase disaster preparedness and humanitarian relief as well a means to improve quality of life for rural marginalize populations.

DECLARATION

I, Thomas Joseph Nicholson, hereby declare that this Master of Science (Pharmacy) thesis is entirely my own original work and that, all other works mentioned in this document are referenced appropriately so. I further declare that, this work has not been submitted elsewhere for a higher degree application.

Signature:……………. Date:…………………

ACKNOWLEDGMENTS

Firstly, I would like to thank my supervisor Dr Roman Tandlich and co-supervisors Dr Nosiphiwe Ngqwala and Mike Wisch for accepting me as a Masters student and for being instrumental in completing my project. Even when times were tough and I had made mistakes, you still believed in me and trusted me to learn from my mistakes. You were always there for guidance, no matter what time of night or day. Your calmness in challenging situations was the only thing from keeping me from pulling my hair out at times. Secondly, I would like to thank the Environmental health and Biotechnology research group. I have never been part of such a supportful group, when confronted with challenges in and out of the lab I could always rely on each of you for advice and guidance. Each one of you has been key in surviving the last 18 months. Special thanks to the Rhodes University Pharmacy department for providing all the necessary materials used.

To my parents, Merle and Joe, I literally couldn't thank you enough. Thank you for always supporting me in all of my endeavors. I thank my blessings every day to be able to study what I am interested in and that is only because of the sacrifices you have made. I love and appreciate you more than I can express.

To my high school biology teacher, Jenny Kirn, your passion towards all things biological influenced me to go down this path. You believed in me and I doubt I would be where I am today if it wasn't for you. I was always interested in living systems, but it was you who made me realize I wanted to donate a portion of my life towards studying, understanding and ultimately manipulating them in the field of biotechnology.

DEDICATION

I dedicate this Master of Science (Pharmacy) thesis to my loving and supporting parents Merle and Joe Nicholson.

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LIST OF ABBREVIATIONS

AC	Alternating Current
AIDS	Acquired Immunodeficiency Syndrome
API	Analytical Profile Index
ASTM	American Society for Testing Materials
BB	Battery Bank
BNG	Breaking New Ground
CDC	Center for Disease Contol and Prevention (United States)
CFU	Colony Forming Units
COD	Chemical Oxygen Demand
COE	Cost of Energy
CRF	Case Report Form
DC	Direct Current
DD	Disease Diagnosis
DEAT	Department of Environmental Affairs and Tourism
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity
EDRU	Enteric Disease Research Unit (National Institute for Communicable Diseases, RSA)
EDT	Eastern Daylight Time
EEM	Energy And Water Emergency Module
ELISA	Enzyme-Linked Immunosorbent Assay
EVD	Ebola Virus Disease
FMDV	Foot And Mouth Disease Virus
GDP	Gross Domestic Product
HIV	Human Immunodeficiency Virus
HOMER	Hybrid Optimization Of Multiple Energy Resources
HWTS	House-hold Water Treatment Systems
JMP	Joint Monitoring Programme
KZN	Kwa-Zulu Natal

MDG	Millennium Development Goals
MRC	Medical Research Council
MW	Mega Watt
NASA	National Aeronautics and Space Administration
NHBRC	National Home Builders Registration Council
NHLS	National Health Laboratory Service
NHREC	National Health Research Ethics Council
NICD	National Institute for Communicable Diseases
NMMP	National Microbial Monitoring Programme
NPB	Net Present Benefit
NPC	Net Present Cost
NPV	Net Present Value
NREL	National Renewable Energy Lab
NUSIPR	National University System Institute for Policy Research
NWA	National Water Act (No. 36 of 1998)
NWRS	National Water Resource Strategies
O&M	Operation and Management costs
PCR	Polymerase Chain Reaction
PCU	Process Control Unit
PHEIC	Public Health Emergency of International Concern
PMG	Parliamentary Monitoring Group
PV	Photovoltaic
RDP	Reconstruction and Development Program
RDT	Rapid Diagnostic Tests
RHPS	Remote Hybrid Power System
RO	Reverse Osmosis
RPA	Recombinase Polymerase Amplification
RSA	Republic of South Africa
RT-PCR	Reverse Transcriptase Polymerase Chain Reaction
SANS	South African National Standards
SANTACO	South African National Taxi Council
SROI	Social Return on Investment

TB	Tuberculosis
TDS	Total Dissolved Solids
TEA	Techno-Economic Analysis
TEU	Twenty-foot Equivalent Unit
UDDT	Urine-Diverting Dry Toilet
UN-ISDR	United Nations International Strategy for Disaster Reduction
UNHCR	United Nations High Commission for Refugees
UNICEF	United Nations Children's Emergency Fund
UV	Ultraviolet
W	Watt
WAS	Western Area Surge
WCM	Water Compliance Monitoring
WHO	World Health Organization
WSR	Water Service Regulation
XRD	X-Ray Diffraction
ZAR	South African Rand

LIST OF PUBLICATIONS

Nicholson, T.J., Dube, T., Ngqwala, N. P., Tandlich, R. (2016). The importance of power and potable water in the public health: consider solutions in developing countries. Conference proceedings, Public Health Conference 11-13 July 2016, Kuching, Malaysia.

Nicholson, T.J., Ngqwala, N. P., Tandlich, R. (2016). An energy, water and disease disaster management module: A techno-economic feasibility analysis. Conference proceedings, DMISA Conference 21-22 September 2016, ATKV Goudini Spa, Cape Town.

LIST OF CONFERENCES

11th Public Health Association of South Africa (PHASA) Conference: Sustainable Development; The Future. A disaster management strategy to address intermittent power and water supply and a concomitant disease outbreak. ICC, Durban, October 2015, oral presentation.

6th Interdisciplinary Postgraduate Conference (IPGC), A disaster management strategy to address intermittent power and water supply and a concomitant disease outbreak. Gavin Relly Postgraduate Village - Grahamstown, October 2015, oral presentation.

2nd Community Engaged Learning Symposium (CELS), A disease diagnosis and citizen-input approach to address inadequate water supply to rural areas in South Africa. Gavin Relly Postgraduate Village - Grahamstown, May 2016, oral presentation.

32nd Disaster Management Institute of South Africa (DMISA) Conference. An energy, water and disease disaster management module: A techno-economic feasibility analysis. ATKV Goudini Spa – Cape Town. September 2016, oral presentation.

12th Public Health Association of South Africa (PHASA) Conference: Achieving the sustainable development goals. A decentralized disease diagnosis and water compliance monitoring module for public health improvement. ICC, East London, September 2016, oral presentation.

CHAPTER I: BACKGROUND

1.1. THESIS OVERVIEW

1.1.1. MOTIVATION

Inadequate water supply is a major public health concern in many rural areas in South Africa and the world. It may be indicative of poor municipal supply or may result from a sudden emergency occurrence. In either situation, if there is not a swift and sustainable intervention the lack of sanitation and water supply may lead to disease outbreaks. The minimum volume of water per person per day is 50-100 Litres according to the WHO guidelines (WHO, 2011). Developing countries are often substantially more affected by disasters than developed countries due to inadequate disaster-preparedness structures and insufficient finance (Watson *et al*., 2007). The onset of diarrheal illnesses is common after disasters due to contamination associated with damaged infrastructure and inadequate displacement locations. A diarheal outbreak of greater than 17 000 cases, caused by *Vibrio cholera* and *Escherichia coli*, was observed in the post-flood of Bangladesh in 2004 (Qadri *et al*., 2005). A disaster management strategy should be able to address both the lack of water supply and the result of the sanitation concerns arising from it.

1.1.2. AIMS AND OBJECTIVES

The approach of this thesis is to address the water and sanitation concerns caused by poor municipal supply and a disaster situation as holistically and sustainably as possible. The two main concerns highlighted to best address these are water compliance monitoring as a means of prevention and disease diagnosis to allow for timely response and cure. The focus of the intervention is to utilize these functions in disaster management situations; because of this mobility and self-sufficiency of the laboratory unit must be taken into consideration.

Aim: to develop a self-sufficient mobile laboratory capable of water compliance monitoring and disease diagnosis.

Objectives:

1. Structure of the laboratory
2. Power supply
3. Water supply
4. Waste disposal
5. Water compliance monitoring
6. Disease diagnosis
7. Techno-economic analysis

The objectives are listed in the order in which they will be addressed, the specific reasons behind the order of processing in explained in depth in the thesis organization.

1.1.3. THESIS ORGANIZATION

The nature and complexity of the problems and solutions that need to be addressed vary from concomitant information processing to navigating bottlenecks. The thesis is separated into six chapters namely; Chapter 1: Literature review; Chapter 2: Technical design of emergency laboratory module; Chapter 3: Functions of emergency laboratory module; Chapter 4: Simulation, optimization and economic analysis of laboratories and Chapter 5: The effect of fly ash on simulated human faeces. For each of the chapters there is an explanation of the decision-making process and reasoning under the chapter heading; this is to help the reader have a clear indication of the purpose of the section. The overall motivation and need for a laboratory unit is first described in chapter 1, the criteria for the selection of technology is also described and the set of assumptions used is listed; the selection of the equipment and its mentioned in the subsequent chapters according to these criteria. Mobility of the laboratory unit is the most important and is addressed first in Chapter 2, in which details the exact dimensions of the unit and the reasons for the selection. The dimensions of the laboratory unit serve as a size requirement bottleneck for the choice of technology to fulfill the other objectives. A small unit (20ft container) was selected so as to prove the concept with very limited space. Within chapter 2 the next most essential processes are addressed; power supply is focused on first because no other processes can continue without this forms a bottleneck, where there is a trade-off between size requirement and power output. Water treatment and waste disposal are the next technological areas addresses in chapter 2; the selection of treatment technologies is made taking into account the limitations previously set out and the assumptions mentioned in chapter 1. The reason behind this order of processing is also why water treatment and waste disposal technologies are addressed before water compliance monitoring and disease diagnosis. This is because the laboratory requires a human operator and the human operators' needs are addressed first in the order of water supply and then waste disposal. Chapter 3 details the functions of the laboratory and consists of three sections namely, the theoretical disease diagnosis and water compliance monitoring and the experimental bacterial determination from ice samples. Water compliance monitoring addresses the shortfalls in current systems and outlines a solution utilizing alternative more efficient technologies to perform the same outcomes. Disease diagnosis addresses the communicable but more specifically the waterborne disease outbreaks of high prevalence in South Africa and the inexpensive rapid diagnostic kits on the market. Special emphasis is placed on using equipment that is not energy intensive as this power supply is the next bottleneck to be addressed. As a proof of concept, the bacterial determination down to species level is performed in ice samples from common retailers using the API 20E test kit. This is important to show the bacterial identification capability of the laboratory with limited equipment in a field deployment situation and also because this methodology has applicability in monitoring the quality of ice used in experiments; this is important because, ice for laboratory use will have to be procured locally due to the energy intensive nature of ice-makers. Chapter 4 examines the economic viability by determining the costs and social benefits of the implementation of mobile laboratories. Three laboratories with different designs and functions are simulated and optimized and then compared with each other. The energy system is modeled in Grahamstown over a one-year period; the results take into account energy generation and load usage of selected systems as well as capital outlay. The operational and management costs are optimized against energy production and a social return on capital investment is calculated using the social return on investment model. Chapter 5 examines an alternative human waste processing technology with the novel combination of simulated faeces and fly ash as the treatment additive; this is a necessary on-site waterless treatment alternative for the human waste produced by the laboratory operator and has applicability to point-of-use waste treatment. There is a conclusion to the research performed at the end of each chapter.

1.2. INTRODUCTION

A disaster is defined as "a serious disruption in the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources". The Germanwatch Global Climate Change Index stated that of the top ten countries most affected by disasters from 1995 to 2014, nine of those were developing countries (Kreft *et al.*, 2014). According to the United Nations High Commissioner for Refugees, 38.7 million people were being supported by humanitarian relief by mid-2013 (UNHCR, 2013). For displaced humanitarian relief camps, in the instance of a disaster; energy, potable water and adequate waste disposal are the most essential basic needs and human rights (Nerini *et al.*, 2015).

A disease outbreak may occur at any point, often prompted by sub-standard environmental conditions such as inadequate water supply, which may be associated with cholera and typhoid fever (UNICEF, 2014). In 2008, a cholera epidemic prompted by inadequate water supply occurred in Zimbabwe. Fatalities were above the international norm of 1% stipulated by the World Health Organization (WHO, 2007). The disease outbreak was catalyzed by sewer pipes in disrepair, inadequate water supply for prolonged periods and subsequent faecal material accumulation and lack of treatment in rural areas; the major cause for sanitation concerns (Chambers, 2009). The conditions experienced in Zimbabwe are not dissimilar to those of disaster and refugee camps and in South Africa, similarly, infrastructural problems are leading to the microbial contamination of water (Luyt *et al.*, 2012); and in 2010, 47.6% of South Africans experienced water outages and, of these 36.2% were for prolonged periods (longer than 15 days) (Statistics South Africa, 2011). This creates a need, not only to have the capability to manage a disease outbreak by providing the necessary needs such as potable water supply, but to monitor water supply for microbial contamination as for a means of prevention (Lewin *et al.*, 2007).

Currently the Water Service Regulation (WSR) (Section 62 of the Water Service Act 1997) is the underpinning legislation responsible for compliance monitoring of potable and wastewater in South Africa. In 2008, the incentive based Blue and Green drop potable and wastewater compliance certificates respectively, were introduced to address ill-monitored water sources (DWA, 2009). The regulation of water providers and wastewater treatment systems is imperative to minimize public health risk and environmental damage. The Blue drop accreditation is indicative of procedural, chemical and biological compliance of potable water from a service provider. The Green drop accreditation displays highly efficient wastewater treatment systems (DWAF, 2013). Despite some metropolitan municipalities thriving with this new incentive based approach, many rural municipalities were not able to meet the minimum requirements. The lack of compliance is mainly due to lack of skills and resources and mis-understanding of the necessary standards and inadequate intervention from regulatory authorities (DWA, 2012). Biggs *et al.*, (2009) suggests that the major difficulty is the mismanagement of already limited resources within the rural municipalities (Biggs *et al.*, 2013). With the inability of the majority of rural municipalities to comply with regulatory standards, it is a question of when and not 'what if" a major sanitation concern and possible disease outbreak will occur. In the United States of America in 2012, there were 73 outbreaks of waterborne disease resulting in 1261 cases of illness (Dewey-Mattia *et al.*, 2013). The rate at which diagnosis and subsequent treatment is varied from area to area and in most cases formal diagnosis of waterborne disease does not occur (Dewey-Mattia *et al.*, 2013). The major need for water compliance monitoring is not being met by individual rural municipalities in South Africa; a possible solution would be a mobile laboratory capable of performing independent water compliance monitoring as well as the capability to treat non-compliant water to within compliance.

Apart from cause-specific disease outbreaks, there can also be pathogen epidemics such as the recent Ebola virus disease outbreak in West Africa in 2013 (Briand *et al.*, 2014). The outbreak of Ebola virus disease (EVD) in West Africa in late 2013 was declared a Public Health Emergency of International Concern (PHEIC) by the World Health Organization (WHO) (Briand *et al.*, 2014). As of April 18, 2015, there are 14889 laboratory confirmed EVD cases and 10730 confirmed deaths. Of these, 11323 laboratory confirmed cases (76.2 %)

and 9592 deaths (89.4 %) were confirmed by international mobile laboratories situated in West Africa (Briand *et al.*, 2014). In Sierra Leone (high outbreak area) there were 13 international mobile laboratories established by January 2015, before which, there were only 5 at the end of December 2014. Operation Western Area Surge (WAS) successfully established 8 additional mobile laboratories between the 6th of December 2014 and the 15th of January 2015 (Zhang *et al.*, 2015). According to Zhang *et al.*, (2015), the three weeks post the 15th of January 2015 has seen a 39.0 % increase in the number of samples tested (Zhang *et al.*, 2015). This highlights the great importance of mobile field laboratories in the diagnosis stage of epidemics and the ability to provide preventative measures (Inglis, 2013).

Transport or self-presentation of the patient to treatment site for phlebotomy is a major challenge along with the transport time needed of the sample to a diagnostic laboratory equipped to run molecular diagnostics (Moghadam *et al.*, 2015); these could be overcome with a displaced mobile laboratory. Moghadam and colleagues (2015) identifies that field deployment of rapid diagnostic tests in geographically isolated areas could fast identify individual's positive for EVD in their community and therefore better the chances of survival. The World Health Organization identifies the diagnostic tests that can be used to confirm symptoms of EVD; these tests include antibody-capture enzyme-linked immunosorbent assay (ELISA), antigen-capture detection tests serum neutralization test, reverse transcriptase polymerase chain reaction (RT-PCR) assay electron microscopy and virus isolation by cell culture (Bhadelia, 2015). Having highlighted these diagnostics tests, the laboratory should contain the capacity to handle all the laboratory specimens in their recommended storage conditions as this ensures accurate results (Bhadelia, 2015).

In South Africa, the National Health Laboratory Service (NHLS) is responsible for diagnostic pathology service for provincial and national health departments (National Health Laboratory Service, 2016a). One of its key services is in the diagnosis of communicable diseases, such as EVD. Due to billing problems, the department of health of Kwa-Zulu Natal and Gauteng were in substantial debt with the NHLS throughout 2014. The financial issues resulted in impaired diagnostic testing for many clinics in KZN in 2014 and a subsequent request to the National Treasury to rectify the situation was made (National Treasury, 2014). The NHLS is responsible for diagnostic testing for Human

Immunodeficiency Virus (HIV) and Tuberculosis (TB); both communicable diseases require rapid diagnostic testing (National Health Laboratory Service, 2016a). According to a recent press release from the NHLS, Health Minister Aaron Motsoaledi states that through new payment mechanisms and stringent penalties the historical debt is being resolved (NHLS, 2015). Looking forward, if the NHLS were to fall short again, a disaster management strategy might have to account for the flagship HIV/AIDS and TB programs that are in operation as well as account for waterborne disease outbreaks.

Earthquakes are unavoidable natural disasters that can affect large groups of people. Due to the unpredictability of their onset, it is challenging to provide preventative measures. The UN-ISDR aims at providing strategies to offer post-relief for disasters of this nature; their strategies place emphasis on post-event emergency shelter and humanitarian relief camp establishment (Anhorn and Khazai, 2015). An earthquake occurred in 4 regions of Nepal in 2015 affecting approximately 8 million people; of which 7,557 fatalities and 14,409 injured people were subsequently reported in May of 2015 (Khazai *et al.*, 2015). With an estimated 2.8 million people being evacuated from damaged areas displaced emergency shelters were a necessity. Even in the more unaffected cities, power is limited with most residences relying on generator-supplemented supply (United Nations, 2015). Of the 269 relief sites, none have sufficient water supply, and, many are lacking in supply and/or require boreholes to access water. This is not ideal because the sites are for short-term displacement and also because the water would require additional treatment (Khazai *et al.*, 2013). As of the UN situation report No. 20 published in June 2015, potable water was delivered to 1,028,849 people in Nepal; 34,978 people have received sustainable water interventions and 566,617 people have been given access to sanitation kits (Office for the Coordination of Humanitarian Affairs, United Nations, 2015). Many areas are still without adequate water and sanitation; relief organizations have not been able to access 7 village development communities in Dhading and 11 in Dolkaha due to damaged road which has major implications on waterborne disease outbreaks (Anhorn and Khazai, 2015; Office for the Coordination of Humanitarian Affairs, United Nations, 2015). In addition to infrastructure damage in disaster situations there is often a breakdown in power provision to the affected area; this severely impacts energy-dependent water treatment systems. Water treatment systems that do not require a grid-supply or have a renewable source of energy are preferable. When considering earthquakes, access to certain areas is often limited by damage to infrastructure; in some cases areas may only be accessed by air in which cases, the dimensions and mass of the water treatment system should be considered (Frechen *et al.*, 2011). Furthermore, the majority of water treatment systems only allow for interim disinfection and unhygienic conditions in humanitarian camps may result in post-treatment contamination; it is therefore preferable to provide water treatment at the point of consumption. Similarly, in rural areas and informal settlements in South Africa inadequate infrastructure often leads to post-treatment contamination (Carden *et al.*, 2007). This emphasizes the need for point-of-use water treatment as a means to prevent inadequate water supply and sanitation in both humanitarian relief camps and in rural areas in South Africa.

In order for adequate disaster management, decentralized mobile laboratories as defined by Saito and Aoyama (1989) are imperative (Saito and Aoyama, 1989). Typically, with regard to mobile labs in humanitarian relief situations, energy needs are provided for by diesel generators and potable water supply is sourced from central locations; this is expensive and highly reliant on fossil fuels (Nerini *et al.*, 2015). Currently water and power are in short supply in South Africa; this calls for a mobile laboratory, which in protracted situations, in addition to providing diagnostic services, potable water supply and compliance monitoring can provide both energy services, for itself and others. Mobile, decentralized laboratories may be able to address the sanitation concerns caused by inadequate power and water supply in this manner (Nerini *et al.*, 2015).

1.3. POWER SUPPLY

With the increase in globalization energy needs have increased substantially in developing countries. The development of these countries is dependent on the economic growth in the form of Gross Domestic Product (GDP), which is directly related to the power generation capacity and therefore the resources available (Tummala *et al.*, 2016). The increased scarcity of fossil fuels and carbon emission related climate change has prompted a global effort to preserve the environment and conserve energy sources (Vine, 2008). The primary short-term focus is to reduce utilize more efficient technology and processes to reduce the overall energy need (Martiskainen and Coburn, 2011). The secondary focus is to increase renewable energy supplementation in the long term, with both large and small-scale interventions (Zhou *et al.*, 2010). Energy is not considered a sustainable commodity in South Africa due to the reliance on fossil fuels such as coal (Baker, 2015; Fine and Rustomjee, 1996). Currently Eskom, the primary electricity producing government-owned company produces 95 % of South Africa's electricity and 45 % of electricity consumed in Africa (Baker, 2015). Poor maintenance of power plants has led to a less-than-capacity power output and the collapse of a silo that produced 10 % of Eskom's total power output (Giglmayr *et al.*, 2015). South Africa is the largest energy producer in Africa with a capability of 43 300 megawatts per day, the closest to which is the 29 000 megawatts per day produced by Egypt (El-Zonkoly, 2015). Due to infrastructure defects, poor maintenance of current plants and delayed production of new plants the energy capacity was at an average of 71 % of the energy demand of approximately 40 000 MW per day (Giglmayr *et al.*, 2015). The situation led to the process of "load shedding" in 2015 whereby the available power was distributed, with certain areas being denied power for several hours a day on a schedule; this was to reduce load on the stressed power plants (Correia and Koch, 2011). If the process was not strictly performed on a day-to-day basis this may have lead to a complete blackout. Currently, in 2016 the power producing capability has been stabilized by the distribution of load to several power plants however recent strike action might hamper the production of power and lead to further bouts of load shedding (le Cordeur, 2016). The power situation in South Africa is still considered fragile.

Eskom warned government officials in 2014 that if the system were to shut down it would take two weeks or longer to regain power output. This approximation was based on the power shut down that occurred from Arizona to Southern California in 2011 (Miles *et al.*, 2013). On September the 8th, 2011, an 11-minute system disturbance lead to a cascading power outage affecting parts of Arizona, Southern California and Baja California, Mexico, subsequently leaving an estimated 2.7 million housing units without power (Miles *et al.*, 2013). Of the major districts affected, San Diego Gas and Electric took 12 hours to restore its 4,293 MW load, Comisión Federal de Electricidad took 10 hours to restore 2,150 MW of its load (Miles *et al.*, 2013). Considering the load Eskom requires would be substantially larger than that restored by districts in California, it would take a considerably longer time. In addition, power was purchased from neighboring states to restore the power in each district in California (Miles *et al*., 2013) and currently there is no neighboring country capable of producing the 43 300 MW needed to restart the system. The cause for the Arizona-Southern California outage was due to deviations in the flow of voltage, overloading some systems and leaving others without load. Over the 11-minute power distribution occurrence, transformers, transmission lines and generators were overloaded and subsequently tripped offline (Miles *et al*., 2013). Similarly, if Eskom units were to be overloaded at any point, it may lead to a sustained power outage. In the 12-hour outage, the direct economic loss was estimated to be between 97 and 118 million USD by the National University System Institute for Policy Research (NUSIPR) (National University System Institute for Policy Research (NUSIPR), 2011). The estimates factor in food spoilage, government overtime and lost productivity, all of which are largely based on population and length of the outage (NUSIPR, 2011). The potential economic cost of a total blackout in South Africa will be dependent on the 18-fold population increase and an estimated two-week restoration time.

To give a more accurate estimate of the possible implications of a total blackout in South Africa we can compare it to a blackout of similar magnitude. In 2003 a blackout occurred from Midwest to Northeast United States and in Ontario, Canada that affected over 50 million users (Bo *et al*., 2015), which is similar to the population of South Africa (approx. 53 million) (Statistics South Africa, 2015a). The load lost was 61 800 MW, which is higher than the 43,000 MW load of South Africa. The blackout occurred on August 14th, 2003 at approximately 4:00 pm (EDT) and lasted for 4 days to a week in some areas (Bo *et al*., 2015). According to Bo *et al*, (2015) the reasons resulting in the blackout included outdated equipment, lack of communication between power producers and inadequate surge and stability control measures. Although the majority of power is from one producers which decreases the risk of communication error, South Africa also has outdated equipment and inadequate surge protection according to Swart (2015). A cascading power surge resulted in 531 generators in 263 power plants and many high voltage transmission lines to be tripped offline. By 11.00 am on the 15th of August, 48 600 MW of load had been restored, however emphasis must be placed on the power producing capability of neighbouring states and the load 'borrowed' from them to resume normal operation of power plants. In relation to South Africa, as previously mentioned, the ability to restore maximum load is a substantially more complex situation.

In light of recent conditions, alternative small-scale systems are required to address a power crisis on the domestic level. Hospitals are of primary importance as a power outage can have a direct effect on the ability to provide care for compromised patients. Systems such as generators and boilers are in place for the production of electricity in adverse situations (Bizzarri and Morini, 2006). For private residences, specifically those in newly developed rural areas, a sustained power outage has major implications on sanitation and a disease outbreak might incur as a result (Khazai *et al.*, 2015). Prolonged power outages interrupt water treatment systems and thereby increase the risk of waterborne diseases (Marx *et al.*, 2006). Currently in low-income settlements there are often interruptions in water supply. In addition frequent power outages often hinder the ability to provide adequate water quality supply and sanitation (Moe and Rheingans, 2006). This is of particular importance to the design of a mobile laboratory in South Africa as grid-supply cannot be relied upon; an off-the-grid system for power provision is required. Power self-sufficiency is required in order to ensure the functions of the laboratory are not impeded by a power outage. Furthermore, water supply can be monitored and an intervention can be implemented with the laboratory.

1.3.1. SOLAR ENERGY

The use of solar energy provides distinct advantages; the abundance of solar resource and the lack of pollution are key features, others include the direct conversion of light into energy; the absence of moving items, the lack of maintenance for long periods, long life span, range of power operational capabilities, decentralized applicability, and for mobile use; the high power to weight ratio. A major limitation with using solar systems is the non-linear power production, not producing power in the absence of light, creating a need for a storage system to act as a power supply buffer (Kumaresan *et al.*, 2012). Photovoltaic (PV) cells operate by generating high-energy free electrons from photons via the photoelectric effect and then passing these electrons through a potential difference to produce a current. The process is therefore highly dependent on the ability of a material to absorb light. The light-absorbing medium used in most PV cells is silicon. The crystalline structure of silicon has been shown to have an effect on efficiency of the PV panels. A comparison between the efficiency of multi- and mono-crystalline silicon was performed by Bruton, (2002). Itoh ***et al.***, (2001) showed significant seasonal output differences between the use of polycrystalline-, amorphous- and crystalline-silicon mediums; with 5 % higher energy generated by the amorphous silicon compared to mono-crystalline. In the South African renewable energy market the significant price difference between the mono-crystalline and poly-crystalline variants does not justify the relatively small increase in energy output. With the modular nature of PV panels it is economically preferable to purchase additional Poly-crystalline instead of purchasing mono-crystalline PV panels which are more energy efficient. Bhuiyan and Asgar, (2002) assessed the economic viability of stand-alone PV systems in remote areas in Bangladesh by using a net present cost methodology and estimating the lifespan of the project; the cost of energy (COE) was lower from the PV system compared to the diesel and petrol electricity generation. Kivaisi (2000) showed the successful electrification of a school, health centre and mosque in Tanzania utilizing a 3 kW PV array. A bigger 25 kW PV array was used by Bansal and Goel (2000) to power a cafeteria in Delhi, India. The angle of 20° and 15° (from horizontal) were used respectively and the direction of the arrays was due south. Although both these systems operate in different capacities they both emphasize the feasibility of using PV systems for rural electrification. Assumptions (further mentioned) can be made about the angle, orientation and capacity of the PV system based on the previous authors successes (Bansal and Goel, 2000; Kivaisi, 2000). The success of stand-alone PV systems has promise for use in the context of a mobile laboratory.

1.3.2. WIND ENERGY

Wind is one of the most abundant renewable energy resources in the world; the increasing size of turbines, higher efficiency and lower costs are increasing the economic viability of using wind systems (Thor and Weis-Taylor, 2002). Wind systems have shown promise in off-shore and distributed small-scale connected systems; with constant optimization and improvement of existing systems being shown (Henriksen, 2010). The techno-economic viability of wind power generation is not always optimal due to the unpredictability and irregular occurrence related to the geographic location of the turbine (Henriksen, 2010). There have been many countries that have adopted large-scale wind turbine technology to supplement their energy requirements. China had a cumulative wind energy production of 114 609 MW by 2014. Cumulative energy production from wind resources of 65 879 MW, 39 165 MW and 22 987 MW by other leading producers USA, Germany and Spain was observed respectively (Tummala *et al*., 2016). With the increasing energy demands, large-scale wind farms are required; the offshore London array is 100 square kilometers and onshore 36.5 square kilometer Alta wind energy centre are current examples of meeting increasing demands (Wang and Prinn, 2010). Several authors observed increases in surface temperatures as a result of these large-scale wind farms; this is due to the increased ocean surface drag (Fiedler and Bukovsky, 2011; Wang and Prinn, 2010). From these results it can be concluded that large-scale wind farms have the potential to negatively affect the atmosphere and cause substantial changes in climate. Large-scale wind farms may not be environmental sustainable for energy production. A solution to this is multiple small-scale decentralized wind energy production; small-scale wind turbines can produce up to 10 kW power, which is adequate enough to meet domestic needs. Utilizing this valuable resource would significantly increase energy savings from fossil fuel-based methodologies. In order make use of such systems the limitations of small-scale systems should be evaluated. Some of the aspects to consider are the high capital costs, the operations and control system of wind system along with the site selection and wind velocity data (Tummala *et al*., 2016). Varying wind velocities significantly affect the power output and therefore the return on investment. The economic viability is also greatly affected by height of the turbine and the surrounding structures (Tummala *et al*., 2016).

In the absence of accurate and long-term wind velocity data it is challenging to predict the wind energy output of a given location. Nigim and Parker (2007) were able to assess the power production probability of a site based on the historical wind data. Li *et al*. (2010) used averages of long term historical wind velocity data whilst Zhao *et al*. (2009) optimized the technical specifications, the input parameters and electrical control system of a chosen wind system with standard wind velocity data; giving conclusions of associated costs and reliability. With the use of a small-scale wind system for a mobile laboratory; the geographical location of the laboratory should be considered non-standard. The location is non-standard because the premise behind the mobile laboratory is the deployment in emergency situations, which are generally highly unpredictable. The cost, reliability and size of the wind turbine should be considered and smaller emphasis should be placed on geographical location; this will have to evaluated purely on a case-by-case basis (Jiang *et al*., 2012). For the simulation of wind turbines using meteorological data, it is assumed that power generation begins with the cut-in wind speed for the specific wind turbine; the relationship between the power output and wind speed is direct and linear and the power generation seizes when the wind speed is below the cut-out threshold (Zhou *et al*., 2010). In South Africa the use of wind energy in a project requires a wind resource assessment. For projects involving less than 10 kW turbines there is no compulsory time period for wind data collection however it is advised that 2 years of wind data be used to first evaluate the feasibility of the chosen location (Daniels, 2008; Department of Energy, 2016). A energy system similar to that required was designed by (Nerini *et al*., 2015); two wind turbine systems were modeled, one with a single 2.4 kW turbine and another with two 1 kW turbines. The single 2.4 kW wind turbine (Power Skystream) was shown to be preferable with energy production of 400 kW h/month at an average of 5.4 m/s wind velocity. In South Africa, the most economically viable small-scale wind turbines available are 1 and 3.5 kW (Sustainable Inc., 2016); this is because they are the most popular for residential use and therefore in the greatest supply. In each area of deployment there will be unique topography and therefore optimum wind turbine size will be highly situation specific. For the purpose of modeling and optimization the more economical 1 kW wind turbine is preferable as shown when modeled by (Nerini *et al*., 2015). A small-scale wind system will prove economically viable when it has a comparable cost per Watt and unit cost per kWh to other power producing systems.

1.3.3. BIOMASS ENERGY

With the increase in oil price and the depletion of fossil fuels there is a renewed interest in the use of biomass (vegetable oil) derived biodiesel (Bozbas, 2008). The interest in vegetable oils is prompted by the biodegradable and renewable nature of the resource. In recent years there has be a focus on the more efficient anaerobic digestion coupled biomass gasification process to produce fuel and therefore electricity. The biogas fuel is produced by anaerobic digestion in the process of fermentation of biomass such as wood chips and other easily degradable organics. The biogas collected is used to produce electricity by combustion in an engine (Baños *et al.*, 2011). Biomass energy generation is the production of electricity utilizing biological sources as a fuel. Unlike fossil fuel-based energy production, biomass energy can be produced in an environmentally sustainable way as the carbon emissions are offset by the carbon used by the growth of biomass feed plant (Muradov and Veziroglu, 2008). The use of biomass as a renewable source of energy is a relatively new concept with multiple methods of electricity production; steam from biomass combustion, heat-thermal-electric conversion, methane gas, ethanol and diesel are means by which biomass is used to produce electricity. There are certain environmental concerns with biomass gasification; compounds that affect respiratory health such as nitrogen oxides, particulate matter, tar and aromatic hydrocarbons can be generated during combustion (Kumar *et al.*, 2009). Specific compounds such as benzene, toluene and xylenes are common products of gasification and are directly related to cancer, hepatic problems, anemia and irreversible neurological damage (Hamilton *et al.*, 2014; Snyder, 2012). Hamilton *et al.* (2014) determined the concentration of key pollutants from the most inexpensive biomass gasifier commercially available. The 10 kW power pallet gasifiier-generator system from All Power Labs Inc. (2016) was evaluated using woodchips as a feedstock with a packed-bed tar filter on the engine exhaust. The carbon emissions of 45 to 124 g/kWh was well within the Phase 3 spark-ignited non-road engine (Class II) stipulated 610 g/kWh; the particulate matter generated (0.8 mg/Nm^3) was far below the World Bank guidelines for stationary engines of 50 mg/Nm^3. Significant percentage removal of benzene, toluene and xylene was achieved with the filter as opposed to without, the concentration of benzene was above the National Institute of Occupational Safety and Health (NIOSH) recommendations of 15.9 mg/m^3 for short-term exposure and 3.2 mg/m^3 for 8 hour long term exposure (Department of Health and Human Services, 2007; Hamilton *et al.*, 2014). The reduced producer gases were under 31.9 mg/m^3, which suggested that risk to human health will be minimal if operation takes place in a well-ventilated decentralized area (Hamilton *et al.*, 2014). To evaluate biomass energy generation as a renewable source the sustainability of production must be assessed by price, efficiency, availability, emissions, limitations, land and water use and the social impact. For large-scale generation most of these parameters have been shown to be favourable, with the exception of the high land and water usage and the unfavourable social impacts (Hamilton *et al.*, 2014).

1.3.4. HYBRID ENERGY GENERATION

Hybrid energy generation is achieved with the combination of two or more energy sources; often a renewable source supplemented by a non-renewable source such as a generator. The advantages include decreased reliance on non-renewable fuel sources and the non-reliance on any one particular fuel resource and therefore increasing reliability (Deshmukh and Deshmukh, 2008). For this reason, modeling, simulating and optimizing a hybrid energy generation system for the incorporation into the mobile laboratory is essential to the overall thesis. Barton and Infield (2006) modeled a hybrid system with the incorporation of a wind turbine and PV array with a battery bank to cater for varying electrical loads. They used readily available solar and wind data with probabilistic seasonal and quotidian distribution and predicated load. Generic power production was used for the solar and wind systems. The wind turbine was assumed to be 1 MW with a cut-in velocity of 3 $m.s^{-1}$ and a maximum 13 $m.s^{-1}$. The solar system was assumed to produce the solar irradiance data multiplied by the peak PV production. Reliable results were shown with good storage efficiencies and power producing capacities over loads varying from 1 to 3 MW (Barton and Infield, 2006). Katti and Khedkar (2007) showed greater energy production and efficiency with a hybrid wind and solar system in comparison to wind-alone and solar-alone systems in remote areas whilst using a load following algorithm with system size being optimized. Optimized hybrid systems have been shown to be more cost effective and reliable than single-energy source systems (Klychev *et al.*, 2007). Prasad and Natarajan (2006) showed the optimization of a PV-wind-battery bank system based on system life cycle, relative excess power generated and unutilized energy probability. The design of a hybrid system with multiple energy resources is challenging due the unpredictability of renewable energy resources, the load required from the system and the non-linear energy production from some components. In addition, the evaluation of the system containing non-renewable and renewable energy sources is equally as challenging due to conflicting economic and environmental objectives (Baños *et al.*, 2011). Some authors have addressed this by taking into consideration the technology used, incentives and economic constraints of the system (Lee and Chen, 2009). Zhou *et al*. (2010) suggests that there are a lot of equally accurate techniques for optimizing and integrating hybrid systems with different parameters. Katsigiannis *et al*. (2010) describes the optimization of peak load while minimizing intermittence in a PV-wind-battery hybrid system using a multi-objective algorithm; cost and greenhouse gas emission were also minimized. A similar multi-objective analysis was performed by Bernal-Agustín *et al*. (2006) with the emphasis on total cost, lifespan and emission of the system with a further study focusing on the unmet load (Dufo-López and Bernal-Agustín, 2008). Ould Bilal *et al*. (2010) optimized hybrid systems based on annualized costs and loss of power supply. The solar irradiation and meteorological data was used for the optimization of the system designed by Eke *et al*. (2005). In the design of a hybrid system the size of system and the control strategy should be optimized based on the load required (Dufo-López *et al.*, 2007). Furthermore, the quantity and power output of PV modules, wind turbines, batteries and biomass systems should be optimized along with the PV tilt angle and the wind turbine height (Yang *et al.*, 2008). Several examples of hybrid power production have been shown in remote locations with commercial systems. The PortaWatt units utilize integrated wind and solar systems and a battery bank for electrification in disaster situations (PortaWatts, 2015); similarly, Firefly units utilize diesel and solar resources for electrification (Firefly, 2016). Several medical clinics have been implemented with solar, wind and battery storage in developing countries; Ethiopia, Cameroon, Ghana and Kenya (Higier *et al.*, 2013). Economically, rural electrification was found viable in stand-alone solar, wind and diesel hybrid systems in Ghana which is translatable to the rural conditions experienced in developing countries (Adaramola *et al.*, 2014). The model for decentralized rural electrification in other developing countries is important when considering the feasibility of the mobile laboratory in rural settings in South Africa.

1.3.5. HOMER SIMULATION SOFTWARE

Hybrid Optimization of Multiple Energy Resources (HOMER) is the preferred tool in literature for simulation and optimization of hybrid energy systems. The tool was originally named Hybrid Optimization Model for Electric Renewables and was developed by the National Renewable Energy Laboratory (NREL), USA; it is now licensed and operated by HOMER Energy, USA (2016). The software is capable of performing hourly simulations of a wide range of technologies including PV, wind, fuel cells, hydro and boilers with AC and DC, thermal and hydrogen loads (Sen and Bhattacharyya, 2014). More applicably, HOMER has been used to optimize system configuration in decentralized locations and in developing countries (Sen and Bhattacharyya, 2014). Using HOMER, Givler and Lilienthal (2005) found a PV-diesel hybrid system more economically viable than stand-alone PV and battery systems in Sri Lanka; the HOMER parameters entered were defined as a daily load average of 305 Wh per day, with minimum and maximum loads of 5 and 40 W respectively. Hafez and Bhattacharya (2012) simulated minimum and maximum loads of 600 and 1183 kW respectively amounting to 5000 kWh/day load. The load was used in the hybrid hypothetical optimization of solar, wind, hydro and diesel power producing systems over 24 hours. Whilst Lau ***et al***. (2010) used HOMER to assess the economic viability of different hybrid systems with minimum and maximum hypothetical loads of 30 and 80 kW respectively. Ultimately, despite limitations with meteorological, surface temperature and solar radiance data HOMER has shown to be a vital tool by many authors in modeling and simulating and optimizing off-the-grid hybrid energy generating technology (Al-Karaghouli and Kazmerski, 2010; Givler and Lilienthal, 2005; Lambert ***et al***., 2006; Sen and Bhattacharyya, 2014). In addition the several economic parameters enable the tool to be used to perform techno-economic analyses on optimized systems. Some of the important economic criteria used by HOMER are Net Present Cost (NPC), Levelized Cost of Energy (LCOE) and life-cycle cost. NPC is the total cost for the system of the stipulated project life span and it includes capital, operations and management and replacement costs as well as the annual real interest rate, which excludes the effect of inflation (Dufo-López and Bernal-Agustín, 2005). The LCOE is the ratio between total annualized cost and annual power output of the system; this has a standard value to evaluate the efficacy of hybrid power systems and provides a means for comparison between systems. Levelized

Cost of system and Life-cycle Cost are also frequently used in literature for comparative purposes (Valente and de Almeida, 1998). In addition, HOMER software enables economic analysis taking into account certain external uncertainties such as the price of fuel and the variable length of batteries. This is performed in a sensitivity analysis where effect of these variable factors is shown on each of the economic indicators (HOMER Energy, 2016).

1.4. WATER SUPPLY

A global approach aimed at ensuring access to safe drinking water and basic sanitation was envisaged by the Millennium Development Goal (MDG) 7c which aimed to “halve the worlds population without sustainable access to safe drinking water and basic sanitation” by 2015. According to the WHO guidelines the volume of water required per person per day is 50-100 Litres (WHO, 2011). In the year 2015, 663 million people globally still lack improved drinking water sources and the sanitation target still not met with almost 2.4 billion still lacking improved sanitation facilities and 946 million practicing open defecation. Despite the access to safe drinking water being met, more people are still using unimproved drinking water sources and live in sub-Saharan Africa, while one fifth live in Southern Asia. (WHO/UNICEF, 2015). In light of this, the Sustainable Development Goal 6 is being implemented to “achieve universal and equitable access to safe and affordable drinking water for all” and to “achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations”. These are much more comprehensive and ambitious goals than the Millennium development goals as they aim for the complete eradication of water inequality (WHO/UNICEF, 2015). In line with water disparities in terms of access to clean safe drinking water in South Africa, the WHO/UNICEF Joint Monitoring Programme Report (2015) highlights that, 8 out of 10 people still without improved drinking water sources live in rural areas. The centralized water supply model provides water to urban areas at economically optimal price due to the economy of scale principle. However, several instances have shown failure of these centralized treatment plants to provide potable water that is within the stipulated guidelines fro consumption; this is mostly due to socio-economic factors (Kyessi, 2005).

South Africa is rated as the 30th driest country in the world (Fisher-Jeffes *et al.*, 2014). The lack of infrastructure and maintenance of existing infrastructure makes it challenging to provide every citizen with their right to basic water and sanitation, defined as 50 to 100 Litres of water per person per day (Carden *et al.*, 2007; Howard and Bartram, 2003). Adewumi *et al.*, (2010a) describes South Africa as semi-arid due to low rainfall and substantial evaporation (Adewumi *et al.*, 2010a). Rainfall collection is an important aspect to consider with the current water scarcity situation. Due to geographical variance in rainfall, certain areas may not have the rainfall capacity to supplement other water supplies (DWAF, 2005). The decreased rainfall is also aggravated by climatic change (Mukheibir, 2005). South Africa's mean cumulative annual rainfall is 464 mm per annum from 2010 to 2015 (DWS, 2016); as Adewumi *et al.*, (2010a) described, a large majority (73 %) is lost through evaporation and surface runoff into rivers (DWAF, 2005). This leaves 13 240 million cubic metres per annum (million m^3/annum) (27 %) of usable water, even though this is larger than the 12 871 million m^3/annum total water requirement (De Lange, 2010); a small fraction of the water is collected and stored and of this it may not be potable without treatment. In addition, Mukheibir (2005) has estimated a 10 % reduction in stream flow by 2025 due to increased population and urbanization.

Table 1.1. Top 30 most water scarce countries in the world (adapted from Reig *et al.*, 2013)

Rank	Country Name	Baseline Water stress score	Rank	Country Name	Baseline Water stress score
1	Antigua and Barbuda	5.00	1	Western Sahara	5.00
1	Bahrain	5.00	17	Saudi Arabia	4.99
1	Barbados	5.00	18	Kuwait	4.96
1	Comoros	5.00	19	Oman	4.91
1	Cyprus	5.00	20	Libya	4.84
1	Dominica	5.00	21	Israel	4.83
1	Jamaica	5.00	22	Kyrgyzstan	4.82
1	Malta	5.00	23	East Timor	4.81

1	Qatar	5.00	24	Iran	4.78
1	Saint Lucia	5.00	25	Yemen	4.67
1	Saint Vincent and the	5.00	26	Palestine	4.63
1	San Marino	5.00	27	Jordan	4.59
1	Singapore	5.00	28	Lebanon	4.54
1	Trinidad and Tobago	5.00	29	Somaliland	4.38
1	United Arab Emirates	5.00	30	Uzbekistan	4.32

Table 1.1. displays the top 30 most water scarce countries in the world based on their respective Baseline water stress score. The Baseline water stress score is an annual measure of how much water is used and the amount available; the higher the number the greater the demand and the lesser the supply (Wästerström, 2016). In South Africa since 1994, there are policies being implemented to ensure better management and optimal use of water resources. Policies such as the National Water Resource Strategy (NWRS) National Water Act (NWA), which aims to optimize water use and minimize damage to ecosystem. In South Africa in 2014, the implementation of the NWA had successfully provided 90 % of households with access to piped in their or within 200m of their dwellings which is a major improvement from 84.9% in 2002 (Statistics South Africa, 2015b). However, even though the water supply is there, there is a concern with the irregularity of potable water supply (Luyt *et al.*, 2012). This is largely due to infrastructural problems and incompetent waste-treatment operators, which leads to microbial contamination of water (Momba *et al.*, 2009; Mulamattathil *et al.*, 2015). Hence, a large part of the population may experience intermittent and microbially contaminated water supply and diseases such as cholera and typhoid fever may occur as a result (WHO/UNICEF, 2014). This creates a need to monitor water supply for microbial contamination (Luyt *et al.*, 2012).

When water supply is unavailable or in limited supply residents in rural areas rely primarily on rivers and superficial wells. The digging of wells is often the preferred solution due to the closer proximity, easier access and the perception of good quality water associated with wells (Moyo *et al.*, 2004). In areas with decentralized water supply wells are often used to access water by households, businesses, apartment blocks, hotels and restaurants (Basu and Main, 2001). However, without prior knowledge there can be several problems associated with the construction of these wells, sanitation concerns can occur if wells are placed in close proximity to sources of contamination and if the wells are not deep enough. According to the WHO guidelines for safe drinking water the distance between faecal management systems and drinking water wells should be greater than 30 m (WHO, 2011). In addition, if hydrogeological data is not consulted the depletion of the groundwater table may occur and in most cases groundwater supply becomes brackish due to inadequate drainage (Schmoll, 2006).

In other semi-arid countries rainwater harvesting has become a necessary means to access water supply; in Tanzania it is estimated that 50 % of the water supply is supplemented with rainwater supply (Mbilinyi *et al*., 2005). Rainwater harvesting can occur as a community system, harvesting from roads and fields, or at the point of use, which has the advantage of reducing operations, management and transport costs (Gould and Nissen-Petersen, 1999). In rural areas and refugee camps, rainwater harvesting is significantly more challenging due the densely populated area and little available land (Nassar and Hamdan, 2013). The average cumulative rainfall in Beit Lahia City in the Gaza strip, Palestine is 433 mm, which is similar to the South African average previously mentioned. Nassar and Hamdan (2013) found that majority (43 %) of the citizens in rural areas had access to individual rainwater supply whilst only 6 % of citizens in refugee camps in the same area had access to individual rainwater harvesting systems. In addition, a major disadvantage of rainwater harvesting is the seasonal variance of supply and unreliable varying water quality; bacterial growth has been observed in the storage of harvested water (Zhu *et al*., 2004). Although there are some perceived limitations with rainwater harvesting, having a system in place to access and store the naturally occurring resource is far more beneficial than not. Research has shown that there is no water supply method that display consistent contaminant-free water supply; specifically in rural areas (Vagliasindi *et al*., 2012). Conventional piped-municipal supply is often of inferior quality in rural areas in developing countries and accessing water through wells and rainwater harvesting also has water quality concerns (Gould *et al*., 1999; Mpenyana-Monyatsi *et al*., 2012). In most cases in developing countries water requires further treatment before consumption; in some cases it may require more advanced treatment than others and the method of treatment required is highly situation specific.

1.5. DISASTER MANAGMENT

Safe drinking water has been identified as one of the scarce essential needs in post-disaster relief operations. A rapid response to potable water supply is therefore required to ensure the prevention of waterborne disease outbreaks; in addition to the rapid response a sustainable approach is required to ensure the water supply remains potable (McCann, 2011). Currently, for the most part potable water needs are provided for by bottled water delivered daily and/or water tanker supply. However, for prolonged displacement this is not as sustainable and cost effective as on-site treatment technologies (Loo *et al.*, 2012). On-site treatment technology has been investigated for several disaster management operations (Nerini *et al.*, 2015). The minimum requirements for potable water quality in an emergency response situation are specified in the Sphere Handbook of Humanitarian Charter and Minimum Standards in Disaster Response (McConnan, 1998); no faecal coliforms per 100 mL should be detected; chlorine should be below 0.5 mg/L and turbidity less than 5 NTU. In addition the short term consumption should have no negative effects on the individual (Lantagne and Clasen, 2012). Due to the wide-ranging quality of water in different disaster situations it is unrealistic to provide a one-size-fits-all solution. An important aspect to consider when providing water is the quantity and quality of water required. The minimum requirement for potable water is 2 and 8 L for drinking and cooking purposes respectively per person per day (DeZuane, 1997); whilst the minimum overall requirement is between 100 and 150 L per person per day (Craun and Goodrich, 1999). The treatment capacity of a small-scale system cannot be clearly outlined as it varies according to the situation but Loo *et al.* (2012) defines it as between 1000 and 10,000 L per day.

Research conducted in Nepal, Indonesia, Kenya and Haiti serve as a template for common household water treatment methods (HTWS); these include boiling or chlorination which can be implemented with relative ease (Lantagne and Clasen, 2012). Using methods such as combined flocculation, solar disinfection, ceramic pot filtration and UV light exposure have been also found to be effective in disaster situations (Clasen *et al.*, 2006). These can suffice for emergency response interventions to provide potable water for natural disasters and in response to outbreaks caused by untreated water. In a bid to incorporate easy to use water treatment technologies, Wendt *et al*. (2015) highlights that water treatment technologies such as gravity fed point of use devices and Bio-sand filters have demonstrated the ability to significantly reduce the amount of pathogens in laboratory and field studies with minimal cost (<10 USD/unit-once-off cost) (Wendt *et al*., 2015). Biosand filters have been used successfully in rural communities and studies conducted in River Njoro watershed in Kenya and in the Dominican Republic and displayed significant reduction in days the population experienced diarrhoea (Wendt *et al*., 2015). The biofilter gravity-fed system uses a multiple barrier approach including water bio-filtration and chlorine disinfection. The water is added to the flocculation buck*et al*ong with polyaluminium chloride coagulants and left for approximately 1 hour. The water is then filtered through foam and carbon filterblocks in the second chamber; the water trickles through a chlorine tablet before entering the third chamber (Wendt *et al*., 2015). The lower collection chamber allows for an increased holding time for chlorination. The water then passes through a second carbon filter to remove excess chlorine so the water is fit for human consumption (Wendt *et al*., 2015). The use of chlorination dispensers is highlighted by the work done by Yates *et al*. (2015) on the effectiveness of chlorine dispensers in emergencies in Haiti, Sierra Leone, Democratic Republic of Congo and Senegal. The chlorine dispensers are valve regulated and have the capability to treat adjacent water bodies at the point-of-use. The addition of chlorine is important because of the ease of use in emergency situations and inexpensive immobilization of microbes. The use of chlorine dispensers has displayed significant reduction in the causative agents; ***Campylobacter, Salmonella*** and ***E. coli*** in water supply and a decrease in diarrheal disease (Yates *et al*., 2015).

Loo *et al*. (2012) suggest treating water at the point of consumption based on the findings that residents in temporary relief camps are already exposed to unhygienic conditions, which are further accentuated by the contamination of treated water. Butler *et al*. (2013) identify point of use water treatment technologies as a promising alternative to providing access to safe drinking water in emergencies (Butler *et al*., 2013). In the case of a mobile laboratory deployment, where the exact quality and source of untreated water is uncertain an all-encompassing treatment technology should be considered. Reverse osmosis (RO) is the most widely accepted membrane technology due to the high rejection of contaminants. Although RO systems are preferable in situations where there is no fresh water supply and the water quality is unknown they have a high-energy consumption making it challenging to operate in decentralized locations. This challenge has been overcome with using renewable energy coupled systems (Schäfer *et al.*, 2014). Schäfer *et al.* (2014) identify membrane based water treatment systems as the most appropriate method to remove contaminants from water in decentralized locations. The main membrane technology used consists of microfiltration, ultrafiltration, nanofiltration and reverse osmosis, which are pressure driven processes (Butler *et al.*, 2013). The advantage of this choice for this technology is that it has the ability to remove particles, viruses, bacteria, salt ions, trace contaminants and most importantly, the ability to be coupled with renewable technologies for deployment in the remote areas (Butler *et al.*, 2013). The cost of these technologies vary from 0.7 USD/m^3 for membrane filtration to 18.8 USD/m^3 for reverse osmosis with seawater (Karagiannis and Soldatos, 2008); based on data from 23 African cities the cost of water ranges from 0.1-2.7 USD/m^3 for tap water and 2.4-9.7 USD/m^3 for water tanker supply (Keener *et al.*, 2010); thus making the treatment technologies economically viable if not preferable in certain situations. Theoretically, a proposed laboratory can adopt the use of membrane treatment technology. These systems are a good alternative in the treatment of water however challenges consist in the form of expensive operation and maintenance. Schäfer, *et al.* (2014) advises that issues ranging from the technical operation of such technology need to be addressed before implementation. Training and retention of skilled operators, water quality monitoring, systems failures, technology adaptation, public awareness, finance and sustainability are some of the issues that need to be carefully addressed (Peter-Varbanets *et al.*, 2009). Nerini *et al.* (2015) used a hybrid PV-wind-biomass system to power a 5000 L/day reverse osmosis system off-the-grid. They achieved an Total dissolved solids (TDS) level of less than 42 g/L producing 3421 L of pure water from saline per day operating for 13 hours.

The primary issue with regard to potable water supply in developing countries is microbial contamination (Arnal *et al.*, 2001); which is a major cause of infectious diseases. Contaminated water acts as a carrier of pathogens which when in contact with a host cause waterborne disease infection. Majority of the diseases are due to faecal contamination and therefore poor sanitation. Individuals may become infected from ingesting the contaminated water used for drinking and cooking or from bodily contact from bathing (Gadgil, 1998). Bacterial contamination is not the only source of infectious disease outbreaks; infections are also caused by viruses and protozoa such as ***Salmonella typhii***, ***Vibro cholera***, ***Entamoeba hystolicai***, and ***Cryptosporidium Giardia*** amongst others (Arnal *et al.*, 2001). The presence of faecal coliforms is regarded as indicative of contamination in a water source however, due to the other sources of infection, the absence of coliforms does not necessarily imply the lack of contamination (Gadgil, 1998). A treatment system should have to ability to remove contaminants of any origin. As a means of prevention the laboratory should have the ability to monitor water compliance and diagnose waterborne diseases. A mobile laboratory would be imperative in both the monitoring of microbial contaminants in water supply but to provide an inexpensive means of treating water. However, considering the intermittent water supply, the primary concern is to supply the laboratory with potable water supply itself.

1.6. FUNCTIONS OF THE LABORATORY

The current National Microbial Monitoring Program leaves room for improvement. The current challenges faced by the program include the increased cost of sampling, the increasing sites to monitor together with the topographical distribution and the limited budg*et al*locations (Matthews and Bernard, 2015). A proposed improvement should include the monitoring of remote and rural areas; a possible method for addressing these areas would be with the involvement of citizen scientists for water quality data collection (Dickinson *et al.*, 2010). However, with the use of citizen scientists comes some restrictions; to avoid the possible inaccuracies, a testing methodology that is simple and fairly resistant to user error is preferable. Luyt *et al*. (2012) proposed using a modified H_2S test kit for water compliance monitoring in remote areas.

The colourmetric test kit is used to identify the presence of faecal indicator organisms. A dehydrated media containing $Na_2S_2O_3$ is placed in a sterile urine jar; in the presence of water containing faecal indicator organisms $Na_2S_2O_3$ is reduced to H_2S and a reaction with ferric ions form a black precipitate.

Another test commonly used is the commercially available Colilert®18 system, however for remote locations it is not preferable because it requires the use of an incubator and trained operators. Incubation occurs at room temperature (18 to 25 °C) for the H_2S test kit, which is of particular importance to field operation and more specifically the involvement of citizen scientists as there is not an urgent need to transport the inoculated kit back to the mobile laboratory for incubation. The 18-hour result together with incubator and citizen training required for the Colilert®18 system makes the test inconvenient fro field placement. Citizen scientists will have a short time frame to return the kit and inaccuracies may be present due to insufficient training. Additionally, the absence of an incubator decreases the load on the mobile laboratories renewable energy systems. Although the incubation time is longer with the H_2S test in comparison to the Colilert®18, the test can be done in remote areas by relatively unskilled citizens which decreases logistics such as transport and refrigeration. The bacterial strains accounted for by the H_2S test kits are all of faecal origin and therefore positive tests can be a clear indication of faecal contamination (Luyt *et al*, 2009). In addition, there is no energy required to perform the test, which is preferable for a self-sufficient mobile laboratory and the involvement of citizen scientists.

With the increasing need for point of care disease diagnostic, cumbersome and equipment intensive diagnostic methods associated with Polymerase Chain Reaction (PCR) diagnostics are not meeting the current needs. Newly developed techniques allow for more time-efficient accurate diagnosis in areas where with inadequate infrastructure; due to the infrastructure requirements associated with PCR, most developing countries utilize culture, serology and microscopy for identification of infectious diseases (James and Macdonald, 2015). Peeling and McNerney (2014) estimated that the increase in rapid diagnostic assays to cater for 5 % of the HIV positive population with 90 % sensitivity and specificity it could prevent 180 000 deaths in HIV positive children (as a result of birth from HIV women). This emphasizes the need for rapid diagnostic tests for all infectious diseases. In developing countries the need for inexpensive, energy-efficient rapid diagnostic tests is accentuated by increased burden of disease caused by inadequate environmental conditions. The modern era of diagnostics has made a move towards the combination of rapid diagnostic lateral flow dipsticks and isothermal DNA amplification as an approach in point of care situations. The TwistAmp® DNA amplification kits produced by TwistDx Inc. (Cambridge, United Kingdom) provide simple instructions for the amplification of nucleic acid. The novelty lies in the isothermal 37 °C where the reaction takes place. The equivalent polymerase chain reaction (PCR) would require expensive and energy intensive equipment to produce similar results. The recombinase polymerase amplification (RPA) process developed by TwistDx Inc. allows for end-point of real-time detection by either, gel electrophoresis, fluorescence monitoring of lateral flow assays (TwistDx Inc., 2016). The RPA process uses recombinase enzymes that bind to single stranded DNA/RNA backbones. A copy of the nucleic acid strand is performed from the 3' end of each complimentary strand with the aid of a polymerase. The primers that bind to each end are similar to PCR primers and aid in increasing specificity of the assay (James and Macdonald, 2015). Unlike PCR though, where varying component concentrations require the optimization of kinetics, reaction temperature and product length the TwistAmp® kits are optimized for fast amplification (15 minutes) with an optimum temperature of 37 °C – 42 °C and amplicon length of under 500 bp (TwistDx Inc., 2016). Currently, Twist Dx offers commercially available kits for the quantification of ***Listeria***, Red snapper, ***Salmonella*** and ***Campylobacter***. These kits include all the probes and primers required for the amplification. However, due to the nature of the kit, it can be used to amplify a large variety of viral, bacterial and parasitic nucleic acids; with the design and use of different probes and primers. Additionally, multi-plex amplifications can be performed simultaneously. Recently Crannel ***et al***. (2015) used modified primers and probes with the TwistAmp®nfo to detect the intestinal protozoa ***Giardia***, ***Cryptosporidium*** and ***Entamoeba*** in a multiplex assay. Furthermore, the kits have been modified to detect ***Plasmodium falciparum***, HIV-1, Group B ***Streptococci***, Shiga toxin producing ***E.coli***, foot and mouth disease virus (FMDV) and Ebola virus disease (EVD) (Faye ***et al***., 2015; Ng ***et al***., 2015; Wahed ***et al***., 2015).

1.7. WASTE DISPOSAL

Waste disposal infrastructure in urban areas in South Africa is for the most part in good operation, wastewater is disposed through drainage infrastructure and solid waste is collected routinely by the city council. However, such liberties are not experienced in some peri-urban and many rural areas. In fact in Driftsands, Greenfield, Masipumelela and Tafelsig informal dwellings outside of Cape Town, South Africa, 68% of the settlements did not have a waste bin on their premises (Govender *et al.*, 2011). Of the low-cost housing residents, 8.1% reported disposing excreta and soiled nappies on the streets while 17.8% of informal “dwellers” disposed of these items in storm-water drains (Govender *et al.*, 2011). Additionally, there was only drainage infrastructure for the low-cost housing units, and the informal “shack” inhabitants had to make use of these facilities too. Upon inspection, 92% of the drains of the 173 plots were in disrepair, most likely from over-use (Govender *et al.*, 2011).

Centralized wastewater treatment requires a large amount of infrastructure for collection, treatment and disposal of wastewater which, is expensive to provide especially in already established rural areas (West, 2001). In these cases it is more economically viable in the short-term to provide decentralized small-scale wastewater treatment (Parkinson and Tayler, 2003). In addition to being more economically attractive, the water produced is often of a much higher quality than large-scale treatment plants allowing for reuse in agriculture and therefore decrease overall water usage. Furthermore, small-scale systems are more mobile and can be deployed on a needs basis, providing quicker access to wastewater treatment than large-scale systems. Moreover, small-scale treatment systems are preferable in areas in which there is scattered low-density populations (USEPA, 2007).

With a limited amount of water resources available, there is an ever increasing need to conserve and reuse water, which due to lack of awareness, potable water is being used for non-potable purposes, which subsequently deteriorates the quality of the water (Al-Jayyousi, 2003). In addition, due to the focus of the constitution, officials generally provide water supply before drainage services (Parkinson and Tayler, 2003). As a result of this, wastewater is often disposed of locally, producing large bodies of malodorous, stagnant water, which could catalyze waterborne related disease outbreaks and contaminate groundwater and rivers (Carden *et al.*, 2007; Zuma and Tandlich, 2010).

A primary concern in producing a self-sufficient laboratory unit is wastewater management. In an attempt to understand the requirement for a decentralized method of treating wastewater produced, both in laboratory and housing units, the research units deployed in the Antarctic will be examined. The Antarctic laboratories were only used as a model for service delivery in an isolated settlement. According to the protocol on Environmental Protection in the Antarctic Treaty the minimum requirements for sewage treatment and disposal are prescribed to minimize environmental impact and land occupation and to have a safe and reliable system that is easy to manage (Camenzuli *et al.*, 2015). The above criteria are not dissimilar to those that would be required in a decentralized laboratory unit with an operator.

Despite the requirements of the Protocol on Environmental Protection of the Antarctic Treaty, there is no unified method of treating waste. Some research laboratories are using unique ways of treating waste (primarily human); Belgrano and Orcadas; the two Argentinian bases; separate greywater and reuse it for toilets to reduce water needed (Thomsen, 2005). Dome A, a Chinese base, utilizes a negative pressure 'free-of-flushing' system to reduce the volume of greywater produced (Thomsen, 2005). The Matri and Troll bases of India and Norway respectively utilize incinerator toilets; the ash is collected and disposed of in their respective countries (Thomsen, 2005). Perhaps one of the most efficient techniques used is that of the UK base, Halley VI. They utilize a 'microbac bioreactor' sewage treatment plant, with the aid of modified bacteria, which reduces quantity of sludge produced. De-sludging only occurs once a year, subsequent sludge is incinerated; the ash is collected and disposed of in landfills in the UK (Gröndahl *et al.*, 2009; Thomsen, 2005). With no stipulated method of wastewater treatment in the Antarctic, the techniques of different bases are highly varied. Whilst evaluating Antarctic laboratories some limitations were identified when considering the technologies for implementation in a mobile laboratory. The Antarctic laboratories were often designed with large budgets, which lead to the use of advanced and expensive technology. The energy requirements of many of these systems was substantially greater in colder climates than if it was implemented in a warm climate. The use of Antarctic laboratories examples was important for the modeling of service delivery in decentralized settlements but it is not an ideal model for warmer climates and smaller budgets. In the design of an 'off the grid' lab many aspects should be taken into account, ideally, a technique that is a combination of different techniques needs to be optimized. A key aspect to consider is cost, therefore simple techniques should be of primary importance; hence; a combination of the aforementioned techniques should be investigated.

1.8. ECONOMIC ANALYSIS

In order to determine the feasibility of a proposed system a techno-economic and concomitant cost-benefit analysis is required (Lauer, 2008). The premise behind which is further discussed in Chapter 4. The costs associated with the laboratory can be further divided into initial capital cost and operations and management costs. The initial capital costs will consist of the equipment required and retrofitting the container; the operations and management costs will consist of labour, maintenance and operations cost and the cost of laboratory tests. The Net Present Cost (NPC) will be calculated with all of the above costs and as the total capital required for the entire project for a specified project period (Dufo-López and Bernal-Agustín, 2005). The optimization of the equipment capital and operations and management costs will be determined in the HOMER analysis still to be performed. The optimized costs of the system will need to be gauged against the benefit of the system.

The benefit of implementing a laboratory in decentralized settings is difficult to quantify in monetary terms. The research and development of the prototype laboratory falls primarily into the category of the third sector, in that, although aiding the governmental programs, it is very much a non-governmental and non-profit organization responsible for its implementation. Within the third sector, there has been an increase in the formal standards and performance measures that were previously only attributed to the public and private sectors (Millar and Hall, 2013). Unlike the other sectors, where benefit is more easily estimated in monetary terms, in the third sector benefits are primarily a combination of social, environmental and economic value (Ryan and Lyne, 2008). This is a cause for concern when performing a cost-benefit analysis to determine the economic feasibility measure of a social project. A technique developed by the Roberts Enterprise Development Fund allowed for the calculation of social return on investment (SROI) (Roberts Enterprise Development Fund, 2000). The SROI, since been adapted several times and is now the most widely used method for the calculation of benefit from a social project (Millar and Hall, 2013). Specifically with regard to health and social care, in the United Kingdom Department of Health has encouraged the use of SROI analysis for social enterprises (Millar and Hall, 2013).

There are several guides to perform the SROI analysis, although considering the novelty of the project; the methodology will be modified for this project using information from all sources. It is important to understand the premise behind the methodology. First the necessary stakeholders are identified; this is all populations, organizations and companies that the project is likely to effect. For the purpose of this project the stakeholders are the population of citizens in the placement location and organizations such as the Nation Health Laboratory Service, the Department of Health, Department of Sanitation and Water Affairs, Department of Environmental Affairs, Department of Energy amongst others. For the simplicity of analysis and greater accuracy not all changes will be quantified and not all stakeholders will be addressed; this could otherwise lead to the overestimation of the derived monetary benefit. Once the stakeholders are identified the change, quantity and duration is identified for each stakeholder. Indicators are used to quantify this change for example, increased percentage of people receiving waterborne disease diagnosis and decreased waterborne disease fatalities are indicators of change in an area. The value of this change to each stakeholder is then quantified in monetary terms with the use of financial proxies. Financial proxies are already existing or easily predictable costs that can be used to quantify the value of a particular change to a specific stakeholder (Global Value Exchange, 2016). For the purpose of this project the financial proxies will fall into two major categories namely, the cost of the not having the laboratory in place which will be affected by the percentage deadweight and the cost of another stakeholder providing the same specific benefit to the same area. The percentage deadweight is calculated by defining how much change would have occurred in the specific indicator had the laboratory not been in place, and then dividing this by the amount of change that the laboratory will make. Therefore the lower the percentage deadweight the higher efficiency of the laboratory to provide the change (Global Value Exchange, 2016).

The laboratories will provide for many of the needs of rural placement and humanitarian relief. The process of selecting benefits to quantify in monetary terms is challenging and usually requires input from the selected stakeholders that will benefit from the intended change; however, due to limited time and resources the input of stakeholders was not considered in this chapter. The outcome for each stakeholder was selected from analyzing relevant literature and then these outcomes were evaluated in monetary terms. The valuation process for most projects usually occurs with the aid of financial proxy databases, which house the financial conclusions on different social and environmental costs (HACT, 2016).

1.9. SET OF ASSUMPTIONS

Based on the literature reviewed the following set of assumptions was considered in the decision-making and modeling process. The assumptions were made based on what has previously been successfully performed in literature and the proposed purpose of the mobile laboratory. The technologies were chosen according to their matching the criteria; the best technology for each function was not necessarily chosen due to the availability of systems in South Africa, the financial restrictions of the project and the lack of suitable optimization algorithms.

1.8.1. POWER AND WATER

Solar:

- Poly-crystalline variants are economically preferable over the more efficient mono-crystalline;
- Stand-alone PV systems have lower COE than equivalent load providing diesel and petrol generators;
- PV arrays have shown to power large loads; a standard (relatively small output) panel should be chosen to allow for optimization of number of panels to deal with the load required;
- The PV array should have an angle to the horizontal between 15° and 45° to the horizontal and be orientated due south.

Wind:

- A control system is required to optimize wind system power output;

- The site selection and geographical location of the laboratory should be considered in the simulation process;
- The standard average wind velocity data can be used with good effect in the simulation software;
- The input and output parameters of wind system chosen should be clear; for use in the simulation software;
- Cost, reliability and size of the wind turbine should be optimized further after selection;
- A 1 kW wind turbine has been previously used for modeling similar literature;
- Economic viability should be assessed based on cost per Watt and unit cost per kWh comparisons.

Biomass:

- The sustainability of production must be assessed by price, efficiency, availability, emissions, limitations, land and water use and the social impact;
- The system should provide >10 kWh power output;
- The parameters must be clearly indicated for input into the simulation software.

1.8.2. WATER

Reverse Osmosis:

- The system must be capable of desalination because of unsure situational placement;
- It must be able to operate in conjunction with a renewable energy system;
- It must be capable of treating between 1000 and 10,000 L per day;
- It should not have to operate for more than 10 hours per day;
- It should be able to remove bacteria, viruses and protozoa;
- An impurity level of less than 40 000 ppm if saline water is used;
- It should be comparable the price of available water supply (0.1-2.7 USD/m^3 for tap water and 2.4-9.7 USD/m^3 for water tanker supply)

1.8.3. WASTE

Waste incinerator:

- It should be capable of disposing of medical waste disposal within regulatory requirements;
- It should not have higher emissions than those stipulated;
- It should have the capability to dispose of >10 Kg of medical waste per week;
- It should be Gas operated as it is more economically viable.

1.8.4. WATER COMPLIANCE MONITORING

- The laboratory should have a means for monitoring water in terms of microbial, physical and chemical properties;
- The technique chosen should have high accuracy with limited time and incubation;
- The absence of power reliant technology to perform processes is preferable.

1.8.5. DISEASE DIAGNOSIS

- The laboratory should be capable of waterborne disease diagnosis;
- The techniques used should be non-equipment and non-power intensive;
- They should have high turn-around time- from sample to result;
- The procedure should show high specificity.

1.8.6. ECONOMIC

- The net present cost and project lifespan should be determined;
- A central control system should be optimized in HOMER;
- Values of all the required equipment along with the technical specifications should be noted;
- A novel approach to the SROI method should be considered in the context of South Africa.

1.10. SUMMARY

Ideally, a decentralized unit that is capable of early characterization of a disease outbreak needs to be considered. In the South African context and focusing on power and water supply it is preferable that the mobile laboratory is independent of municipal power, water and waste disposal. The mobile laboratory is required to be self-sufficient in terms of power and water and capable of on-site wastewater treatment. For this reason, inexpensive and energy efficient equipment and process design needs to be implemented and/or designed for optimum energy usage. Aside from this, a similar approach can be applied to low-cost housing; the on-site wastewater treatment will significantly decrease the pressure on municipal systems which will minimize the eutrophication of water bodies and the settlement of large malodorous, stagnant bodies of wastewater. These are significant factors to consider in the prevention of a disease outbreak.

The structure of the laboratory has to be easily constructed, de-assembled and easy to transport among locations in case of disasters. Options for the criterion selection for water treatment technologies that premise on simplicity in terms of use and maintenance stand a better chance for sustainable use in the long run in rural environments (Wendt *et al*., 2015). Renewable energy production sources will be adopted using the criteria of advantages, cost effectiveness, ease of operation, ease of repair and ease of set up and maintenance in relation to cost and technical support. The success of the operations of this laboratory will be on the small-scale renewable energy combinations that provide a stand-alone energy system usually called Remote Hybrid Power System (RHPS) (Sigarchian *et al*., 2014). RHPS are defined as stand-alone power producing systems that utilize more than one energy source; usually incorporating renewable sources like wind and PV systems and non-renewable sources such as diesel generation. Renewable energies have many advantages as they are sustainable and have low emissions and economic benefits (Feroldi *et al*., 2015). The combination of photovoltaic panels, wind energy and batteries is used commonly (Askarzadeh and dos Santos Coelho, 2015). The advent of microgrid technology and remote hybrid power system offer the potential to provide electricity and drinkable water in remote areas and disaster situations (Callaway *et al*., 2014), (Sigarchian *et al*., 2014). The technology uses the same concept of integrating different sources of renewable energy coupled with energy storage units as backup (Sigarchian *et al.*, 2014).

Nerini and colleagues (2015) developed a solution for providing energy and potable water to people in protracted displacement situations. They developed modular components to be incorporated into a shipping container. Their energy module consisted of 22 photovoltaic panels and a battery bank for storing excess power generated. Their system for water purification was a reverse osmosis unit integrated into 2 water storage tanks (Nerini *et al.*, 2015). A study conducted by Callaway *et al.* (2014) modeling a deployable microgrid shares the same concept as the energy and water emergency module demonstration kit in Stockholm (Nerini *et al.*, 2015). Due to the variable displacement situations and therefore weather conditions, Callaway *et al.* (2014) suggests modeling the renewable energy microgrid to integrate energy from multiple systems simultaneously. This will increase power redundancy of the unit and provide a robust short-term power production solution. Kaundinya concluded that a stand-alone energy system for decentralized power production is imperative for optimum operation of the laboratory in a rural setting (Kaundinya *et al.*, 2009).

The containerized solution to meet the energy and water needs for people in protracted situations provides an excellent approach to ensuring security of supply of energy and treatment of water (Nerini *et al.*, 2015). Nerini *et al.* (2015) identifies the constraint to wind system as a "limited power production in situations when there is no wind or when the module is positioned in such a way that surrounding topography creates turbulences in the wind regimes around the wind turbines". This is of particular importance in the South African context as the topography is 'mountainous' and many settlements are densely populated which directly affects the wind resource supply. This decreases the economic viability, as the power generated is not sufficient to provide a suitable return on investment on the capital cost. Schäfer, *et al.* (2014) acknowledges "every technique has its own limitation, and hence the originality of the approach lies in utilizing a hybrid of techniques that tend to cancel the limitations inherent in any one of the used techniques when used on its own". A pragmatic approach in the supply of treated water with particular emphasis to developing countries following the models of industrialized developed nations may not be appropriate (Schäfer, *et al.*, 2014). Options to establish a complete self-sufficient laboratory in a rural setting is possible through the adoption of stand-alone renewable energy systems as they produce greater flexibility in the ability to draw on multiple sources of energy and are more suitable for the rural settings. Water treatment technologies to purify water should be able to be coupled into renewable energy hybrid systems. The utilization of a hybrid of strategies needs to be used in the selection of technologies for the establishment of this laboratory. The hybrid approach ensures that the continuity of operations is conserved even if other systems fail to perform what is expected of them. There is still a lot of research that needs to be conducted for the successful deployment of the laboratory in an African context and more specifically in a rural setting.

CHAPTER II: TECHNICAL DESIGN OF EMERGENCY MANAGEMENT MODULE

Chapter II: Technical design of the emergency management module describes the different design elements that need to be incorporated into the laboratory. Mobility of the laboratory unit is the most important and is addressed first in the introduction along with structural framework, in which the dimensions of the unit and the reasons for the selection are detailed. The dimensions of the laboratory unit chosen serves as a size requirement bottleneck for the choice of technology to fulfill the other objectives. A small unit (20ft container) was selected so as to prove the concept of a mobile laboratory with very limited space. The next most essential process addressed is power supply because no other processes can continue without this and thus serves as the next bottleneck; this forms a trade-off between dimensions and power output. From the previous preliminary design choices a proportion of space in the 20 ft (6 m) container is reserved for water treatment, and waste disposal; following this space is allocated to the equipment needed for disease diagnosis, water compliance monitoring and the laboratory operator. The space considerations used to decide equipment are represented in Fig. 2.1. on page 43. After the equipment was selected the dimensions and physical appearance of each item were used to create a 3D model. Finally, the mass distribution and space utilization optimization of equipment selected is detailed.

2.1. INTRODUCTION

2.1.1. BACKGROUND

A mobile emergency management module is the solution to many displaced needs; because of the nature of mobility of the laboratory, many aspects need to be considered. Designing a single laboratory to address many different situations is challenging; as there may be a situational need for some but not other technologies, for this reason the laboratory will be modulized to offer greater adaptability to the deployment needs. However, for simplicity of this chapter, three different laboratory set-ups will be designed to provide for the needs of different deployment situations. The equipment selection rationale will be based primarily on the 'Sky is the limit' laboratory design aptly named the 'Skye-Lab'; from this the modular approach will address removing components to design the other two laboratories namely, the Eco-Lab and the Grid-Lab. The Eco-Lab will seek to minimize the environmental impact and the Grid-Lab will integrate grid supply and a storage mechanism to ensure power supply redundancy. Although the laboratory capabilities will differ according to the technologies needed for the situation, the underlying structure of the laboratory will remain the same.

2.1.2. CONTAINER DESIGN RATIONALE

A key principle outlined for a laboratory purpose-built for mobile displacement is portability. Shipping containers are designed to be the pinnacle of mobile storage. The shipping container was therefore selected because it fulfills the following key principles:

- Mobility: The laboratory must be fully mobile so as for quick effective movement and placement in emergency situations.
- Flexibility: The laboratory needs to be modulized so that it can be mobilized with the necessary equipment to cater for a specific disaster situation.

Shipping containers are easily transportable, robust and have long life span of consistent use (Pauli, 2010). In order to address the primary concerns the shipping container will be retrofitted with a means of power, water supply and waste disposal infrastructure. Special emphasis will be placed on the modular design and size of components for ease of transportation. For simplicity of design and to prove the mobile laboratory concept with limited space, a 20 ft container will be used as the basis for modulation. In the later stages of development and once the concept has been proved, a 40 ft container may be considered for up-scale. The 20ft shipping container has a load bearing capacity of up to 21 730 kg and the internal dimensions of 5.897mm x 2.348mm x 2.385mm (L x W x H) providing an internal load capacity of 33.08 m^3. These qualities and the dimensions in Appendix A will serve as the basis for the choice of technologies used to provide the other needs. The replacement of equipment should be taken into account when designing and optimizing the loading plan.

2.1.2.1. AVAILABILITY AND PRICING

In South Africa, it is difficult to obtain an exact number of containers retired annually because the shipping companies do not disclose this information. However, an estimate can be calculated based on the number of containers in South Africa and the average annual retirement rate worldwide. In the shipping industry the standard units used to determine the quantity of containers carried by a vessel or in a port is Twenty-foot Equivalent Unit (TEU) (World Shipping Council, 2016). The term TEU therefore describes the use of both 20 ft containers and 40 ft containers, as one 40 ft container is simply considered as 2 TEU. There are approximately 4.9 million TEUs in use annually in South Africa (Transnet, 2015). Considering that at least 81 % of these units are made up of 40 ft containers according to the World Shipping Council, (2016) and with the world average of 5.3% per annum TEU replacement an estimate of how many 20 ft containers retired annually from South Africa can be calculated (World Shipping Council, 2011). The estimated amount of 20 ft containers retired annually in South Africa is approximately 49 343. Comparably, and when considering up-scaling the laboratory, there are approximately 210 357 40 ft containers retired annually. The price of a used container is dependent of several factors according to Gronloh, (2015). Such factors include physical appearance, age, structural integrity and origin of the container and size. In South Africa the price of a >10 year old used 20 ft container in ‘good’ condition is between R15 000 and R21 000 from a reputable retailer, which is significantly lower than a new container, ranging from R35 000 to R50 000 (Container World Ltd., 2016). Comparably, and for up-scale considerations, the price of a used 40 ft container in ‘good’ condition ranges from R25 000 to R55 000. The 20 ft container equivalent is the most readily available and inexpensive to acquire; in addition, the smaller volume allows for the concept of the mobile laboratory to be proven in limited space, which is important for the logistics and cost of transportation.

2.1.2.4. STRUCTURAL INTEGRITY OF CONTAINER

A key feature of the laboratory design is mobility; the purpose therefore is to design a laboratory that can be deployed and re-deployed in different areas based on need. The design of the laboratory must therefore not infringe on its’ structural integrity. The primary process of laboratory movement in which stress will occur is in the lifting, transport and placing procedure. The structural integrity of a container depends largely on the square steel-tube frames, the steel I-beam reinforced floor, the corrugated walls and roof (World Shipping Council, 2016). Together, these components maintain the structural integrity of a shipping container through the compressive and shear forces experienced with lifting and placement. For the longevity of the laboratory through multiple placements the structure of the container must for the most part be conserved. By virtue of laboratory operation and legal accommodation for a laboratory operator the walls of the container will have to be modified to fit the requirements of the equipment selected. When the laboratory is prototyped a strength analysis will need to be performed to determine the deformation of the containers’ structural integrity through multiple movements.

2.1.2.5. LABORATORY OPERATOR ACCOMODATION

The laboratory design will incorporate implementation in a variety of different emergency and disaster avoidance situations. All the methodologies for the tests performed by the laboratory will be chosen with minimal training for the laboratory operator in mind. Regardless, depending on the situational need, either a professional laboratory operator will be placed in the laboratory for a period of time or a citizen scientist will be trained for the permanent operation of laboratory equipment; in either case accommodation for the laboratory operator must be kept in mind.

The National Home Builders Registration Council (NHBRC) stipulates the South African National Standards (SANS) Codes of Practice for all residential projects.

The NHBRC requires a comprehensive report to be submitted for any residential housing based on the requirements. In addition, the laboratory must comply with the SANS10400 codes of practice guideline. The factors that need consideration for the housing part of the laboratory are mentioned below (Department of housing, 1999).

I. Structural performance

SANS10400-2008 states, “Any building and any structural element or component must be designed to provide strength, stability, serviceability and durability in accordance with accepted principles of structural design” (SABS Standards Division, 2008). In accordance with this code the following codes need to be abided by:

SANS 10162: The structural use of steel;
SANS 10100-1: The structural use of concrete;
SANS 10163: The structural use of timber;
SANS 10160: Basis of structural design.
(SABS Standards Division, 2008)

In order to provide the needs for operation the 20 ft container needs to be retrofitted for its purpose. The structural usage of concrete will be required to prepare adequate foundations for the container to be placed on as well as the use of concrete slabs as flooring of the laboratory. The ridged structure of the container allows for the structural use of concrete without affecting the mobility of the laboratory. The roof and mount for the PV panels will require the use of timber and steel respectively. The structural analysis will provide the necessary deformation characteristics with multiple placements.

II. Fire resistance

With the capability of the laboratory to operate high-energy systems along with an incinerator, fire resistance needs to be considered throughout the design process. Particular attention needs to be paid to the fire resistance qualities of the divider walls and the roofing structure. The specific codes of practice will need to be taken account for in the design and building of a prototype laboratory.

III. Water proofing and moisture prevention

With a laboratory operator residing in the unit and the sensitive nature of some tests, water-proofing is essential for the design of the laboratory. The design of the roof must take this and ease of repair into account. Adequate sealing must be applied to all joints of the 20 ft container and the installations in the container walls. The concrete foundation and concrete flooring will act to prevent moisture and dampness. These factors are largely influenced by the humidity of the location. Adequate ventilation is needed as well as a humidity control system in areas where the humidity is excessive.

IV. Insulation

Insulation and thermal conductivity are important factors to consider especially with the energy systems incorporated into the container; special emphasis is therefore needed when considering the insulation of the compartment that houses the energy systems. The insulation properties of different available materials should be examined in the design of the prototype system.

V. Durability

The optimum life expectancy of the laboratory including the energy system should be in excess of 20 years. In order for the laboratory to remain operational for this period of time, with re-locational stresses, the container should retain its structural integrity. The maintenance of structural integrity is stipulated as “retention of performance requirements relating to structural safety and serviceability over the design working life of the house” (National Department of Housing, 2003). This must be taken into account when installing ventilation systems and service hatches in the container walls.

VI. Acoustic performance

Some equipment selected may, in close quarters, exert sound that is above the occupational health standard of 85 db (Center for Disease Contol and Prevention (CDC), 1998); this is of particular importance to the laboratory operator as it may result in an unpleasant work environment but, more importantly auditory damage. According to Botes (2013), sound propagation through a wall is inversely proportional to the density of the wall; in this case the density of the walls that house the equipment need to be maximized to minimize the acoustic noise propagated through the wall. The concrete flooring and insulation selected will serve to mildly reduce noise experienced but ‘sound-proofing’ may need to be considered in the design of the prototype.

VII. Construction of laboratory

The equipment housed in the laboratory will be modular by design and many different laboratory set-ups need to be accounted for. Because of this a method of construction of the “base” unit is needed, within this method every process of construction needs to be considered, from foundation building, interior retrofitting- including flooring, wall insulation and building the equipment housing and the roof fitting. In addition, a standardized lifting procedure needs to be detailed and a risk assessment for the entire construction phase needs to be performed. A form of quality control is also needed to ensure the longevity of each laboratory unit built and ensure the highest quality end product. The International quality assurance standard ISO9001 will be abided by during the production of the prototype to ensure this (Hoyle, 2001).

2.1.3. EQUIPMENT SELECTION RATIONALE

The most important concept of a decentralized laboratory is self-sustainability therefore the first consideration is to ensure the power, water and waste disposal technologies are within the size dimensions of the 20 ft container chosen. The rationale for equipment selection is modeled in Figure 2.1. where the limiting variable is the interior dimensions of the selected 20ft container.

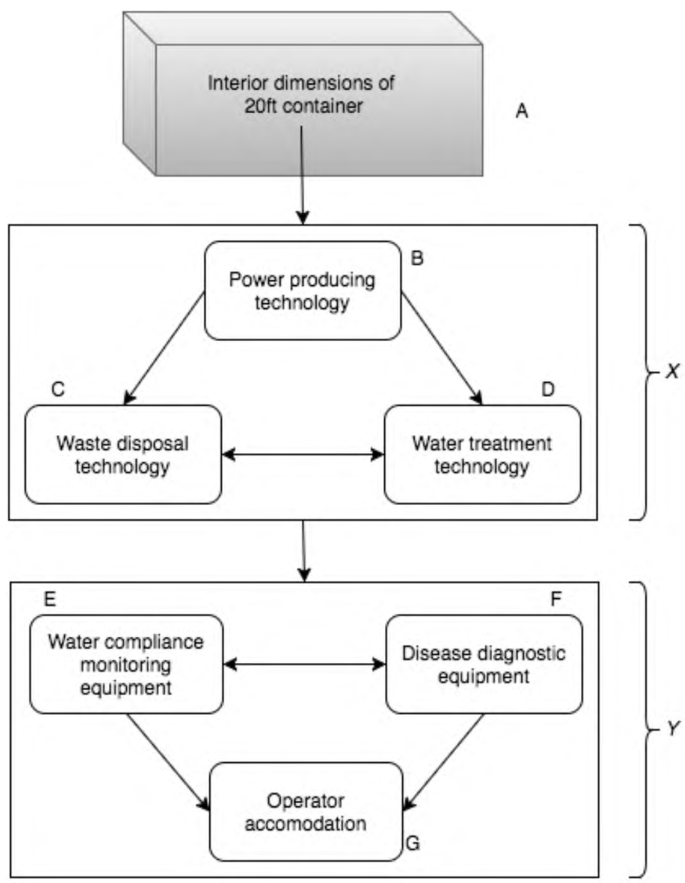

Figure 2.1 Equipment space utilization optimization

In Fig. 2.1., A represents the volume of a 20 ft container (considered 100 % of space available) and B, C and D are efficiency factors calculated by dividing the benefit of the equipment by the percentage space taken up in the container. The efficiency factors were calculated as follows:

$$\mathbf{Ef\ [B]} = \frac{\textbf{maximum kW produced}}{\mathbf{\%m^3}\ \textbf{of container}} \qquad \textbf{[2.1]}$$

$$\mathbf{Ef\ [C]} = \frac{\textbf{kg/hr incenerated}}{\mathbf{\%m^3}\ \textbf{of container}} \qquad \textbf{[2.2]}$$

$$\mathbf{Ef\ [D]} = \frac{\textbf{L/hr produced}}{\mathbf{\%m^3}\ \textbf{of container}} \qquad \textbf{[2.3]}$$

The efficiency factors served as a basis of selection between similar equipment where the higher the factor the more valuable the equipment is in limited space.

For the purpose of allowing ample space for the remainder of the equipment needed for disease diagnosis and water compliance monitoring as well as for a laboratory operator an arbitrary value of no more than 60 % space was allocated to X (Fig. 2.1.). This can be shown by the following algorithm:

$$\mathbf{A_{60\%}} \geq \mathbf{(B) + C + D} \qquad \textbf{[2.4]}$$

Where the B, the power supply equipment was first chosen and the remainder of the 60 % space was given to C and D, the waste disposal and water treatment technologies respectively. After optimization between efficiency and dimensions of the components B, C and D within the 60 % limit the technology to fulfill the laboratories' functions was considered as well as a living space for a laboratory operator. Water compliance monitoring and disease diagnosis equipment were selected based on the percentage of space remaining in the container, their energy consumption and primarily, their specificity and efficacy. Due to the large variability in methodologies used for disease diagnosis and water compliance monitoring and considering a novel approach to these was used, efficiency factors were not used in the decision-making process. Instead portable technologies that used little to no power were chosen. The remaining space from the allocated 40 % was allocated to the equipment used for the function of the laboratory and the equipment needed to house a single laboratory operator.

The primary objective was to provide the necessary equipment for disease diagnosis and water compliance monitoring before the accommodation. The rationale behind this was that the 20 ft container should contain all the equipment needed to serve its deployment needs and that, if space was limiting, other means of accommodation would have been considered. The accommodation was considered based on the necessary legislature previously examined, the needs of the laboratory occupant and the space remaining in the container. The space considerations for Y (Fig.2.1.) can be shown by Eq. 5.

$$\mathbf{A_{40\%} \geq (E + F) + G} \qquad \textbf{[2.5]}$$

The emphasis throughout the theoretical decision-making model should be that the percentage space allocated for each component is to be used as a guideline for packing the container with the necessary equipment and that the percentages are flexible depending on the deployment situation of the particular laboratory. The formulae developed throughout the equipment selection rationale will have an important role when scale-up of the laboratory unit and technology is considered.

2.1.3. EMERGENCY MODULE POWER SUPPLY

Over the recent years substantial research and development has been performed for energy production in disaster situations. Some of the systems currently available include the PortaWatt unit that produces energy through wind and solar systems integrated into a central energy storage system (Nerini ***et al.***, 2015). Firefly units are other transportable energy production solutions that utilize integrated diesel and solar systems (Nerini ***et al.***, 2015). Another example is the clinic developed by Higier *et al.* (2013), which integrates solar and wind power with a system of batteries (Higier ***et al.***, 2013). Perhaps most appropriate, Nerini *et al*. (2015) developed a system to integrate solar, wind and biomass generators along with battery storage with load-bearing water purification technologies (Nerini *et al*., 2015). In the system developed by Nerini *et al*. (2015) a NEDAP central controller was used to harmonize and integrate all sources of power with a singular output. However, to avoid large conversion losses and to incorporate the modular system, the electrical control system will have to be segmented; by ensuring that groups of load bearing equipment have their own supply the conversion losses are kept at a minimum.

To date, no units have been optimized with the use of renewable energy technologies for water purification and laboratory operation in a modular system. The power supply will need to satisfy the following key principles:

- Needs provision: The laboratory needs to provide effective ways to provide power, water and adequate waste disposal for long periods of decentralized placement.
- Laboratory operation: The unit must be capable of providing water compliance monitoring and disease diagnosis for prolonged periods without interruption.
- Modular design: The system must have modular energy components that can be removed or added with relative ease.

Additionally, when modeling the Skye-Lab, within the space limitations of the laboratory the equipment should be able to provide an excess power supply for disaster and emergency situations in which power is required. This is because there is often limited power supply in post-disaster refugee camps (Kaundinya *et al*., 2009). The equipment selected was therefore selected to provide the maximum amount of power per its dimensions as previously described.

2.1.4. EMERGENCY MODULE WATER SUPPLY

In South Africa, there is inadequate potable water supply to rural areas (Mackintosh and Colvin, 2003). It is estimated there are 43 000 fatalities as a result of diarrheal disease annually and costs incurred by the healthcare system are in excess of 3 billion ZAR (Carden *et al*., 2007). This is a major economic and humanitarian cause for concern. In previous disaster management situations around the world, boiling, solar/UV disinfection, filtration, flocculation and chlorination have been the methods of choice for water supply (Clasen *et* *al*., 2006). In addition in many cases potable water was delivered to displaced areas daily. Membrane based purification technologies have become the standard method for producing potable water because of both the quality and quantity of water produced (Peter-Varbanets *et al*., 2009). When selecting a suitable water purifier the following key principles need to be taken into account. The unit should not only provide water for adequate operation of the mobile laboratory but also to the surrounding population as in a disaster management situation. Nerini *et al*. (2015) piloted an energy and water emergency module (EEM) in Stockholm, Sweden using power from wind, solar and generator systems to operate a commercial reverse osmosis (RO) system (Model No. SW-1.3K-425). The prototype EEM built was undersized along with the RO system to prove the concept; the premise was to use a larger system to produce water for 5000 people per day once up-scaled. Similarly, in the design of the Skye-Lab, with the space limitations of the 20 ft container and the equipment needed for the additional processes, the RO system will need to be similar in dimensions to the RO system used by Nerini. If up-scaling is taken into consideration, and a larger container is used, a larger RO system can be implemented. In Stockholm the unit was in operation for 13 hours a day producing 3421 L per day with an energy consumption of 29.25 kWh. Although, Stockholm will differ from the chosen pilot location in South Africa in terms of solar radiance, wind velocity and surface temperature this will only affect the energy systems and not the RO system. The exact RO system used by Nerini *et al*. (2015) or one that compares with the efficiency factor calculated with Eq. 3 will be considered for the mobile laboratory. For optimum water flow the Laboratory unit should be placed adjacent to a water source or, alternatively a borehole needs to be drilled to access the underground water supply. With an important function of the Skye-Lab being disease diagnosis and water compliance monitoring it is within reason that the laboratory be placed adjacent to a water source. In either case, utilizing a water body or a borehole a water supply system such as a pump is also required.

2.1.5. EMERGENCY MODULE WASTE DISPOSAL

With the design and implementation of a laboratory that is capable of disease diagnosis and water compliance monitoring the design must also include adequate waste disposal. The waste disposal can be observed in two major categories, namely medical waste disposal from disease diagnosis and water compliance monitoring; and human waste disposal from the laboratory operator or 'citizen scientist'. Within the context of South Africa, and primarily focusing on water compliance monitoring and disease diagnosis in the rural setting, special emphasis will be given to utilize technologies that can provide waste treatments to the greater community as well as the laboratory. The South African Ministry of Health (1996) identified medical waste management as a significant and highly prevalent concern to address (South African Ministry of Health, 1996). This is because a large portion of this waste is infectious and inadequate disposal may be harmful to the environment and also lead to bacterial resistance. The disposal of medical waste may lead to the production of harmful gases which are also environmental pollutants (Babanyara *et al.*, 2013).

In response, the South African Department of Environmental affairs and Tourism initiated the National Waste Management Strategy to address the issue (South African Department of Environmental Affairs and Tourism (DEAT), 1999). As a possible solution, Lee and colleagues (2004) suggested waste incineration as a low-cost solution to the disposal of medical waste (Lee *et al.*, 2004). Prior to that Brent and Rodgers (1999b) compared the incineration dynamics of low-cost gas, wood and electric powered incinerators. It was found the averaged combustion efficiency of waste to be greatest in the gas and wood powered units with 98.37 and 97.14 percent respectively. Greater variability was shown in the wood fired unit as it was dependent on the quality of the wood obtained (Rogers and Brent, 2006). Due to the variable placing of the laboratory unit there is no guarantee of adequate wood supply as well as the extended use of the incinerator makes it preferable to operate with a gas supply. The gas incinerator developed by Brent and Rogers, (1999b) was piloted with a mobile laboratory in Gauteng, South Africa and is a possible solution to medical waste disposal needs (Brent and Rogers, 1999b). Quantitative analysis on the unit was performed and it was shown to render all medical waste non-infectious and medical instruments unusable. The temperature reached was between 800 °C and 1100 °C with an average waste combustion efficiency of 98.37 %. Conclusions from qualitative analysis performed with laboratory technicians resulted in only 2 hours of operation per week to destroy approximately 10 kg averaging at 1 hour per kg of medical waste generated (Rogers and Brent, 2006).

Within the current legislation in South Africa, the particulate emissions from large medical waste incinerators of 180 mg/Nm^3 is below the stipulated value (South African Department of Environmental Affairs and Tourism (DEAT), 2004). With the infrequent operation of small-scale medical waste incinerators, there are substantially less emissions overall, although the emissions per use are higher with 360 mg/Nm^3. Small-scale incinerators are operated an average of 1 – 3 times a week for 2 – 3 hours whereas large-scale incinerators are in operation 8 hours per day, 5 days a week (Rogers and Brent, 2006). Due to the difference in frequency and length of operation the use of small-scale incinerators should not be governed by the same regulations as large medical incinerators. The South African guidelines for waste incineration are shown below in Table 2.1. These parameters were taken into account in the selection of the incinerator system.

Table 2.1. South African incinerator guidelines (Adapted from Rogers and Brent, 2006)

Parameter	Unit	South African guideline
Stack height	m	3 m away from nearest building
Gas velocity	m/s	10
Residence time	s	2
Minimum combustion zone	°C	>850
CO_2 at the stack tip	% vol	8.0
Gas combustion efficiency	%	99.99
Particulate emissions	mg/Nm^3	180
Cl as HCl	mg/Nm^3	<30
F as HF	mg/Nm^3	<30
Chromium (Cr)	mg/Nm^3	0.5
Manganese (Mn)	mg/Nm^3	0.5
Nickel (Ni)	mg/Nm^3	0.5
Vanadium (V)	mg/Nm^3	0.5

2.1.6. DESIGN OF EXAMPLE LABORATORIES

Because of the varied nature of disaster and emergency situations, the premise behind the laboratory design is to have a modular system in which components can be incorporated and removed based on need. This modular system was considered throughout the design process and is explained in the rationale behind certain equipment selection in the results of this chapter. However, for comparative modeling purposes and to explore more real-world scenarios three laboratories were designed; the laboratories serve a certain function and have the incorporation of equipment that meets that function.

The first model, aptly named the Skye-Lab, was developed with a "Sky is the limit" approach, in which all equipment was incorporated into the design with little to no economic viability taken into account. The equipment served to provide maximum functionality with the only limitation being the space within the 20 ft container. This model is important because it outlines the capability limits of the systems in limited space and provides the upper limits of capital considerations. The majority of equipment selection was based on this model as explained within the considerations for each piece of equipment.

The other two models, Eco-Lab and Grid-Lab, were permutations of the equipment selected, and were designed with a particular function in mind so as to create a 'real world' experience. The rationale and function of these laboratories is detailed in to modulation section of the results.

A standard 20 ft container was selected as the unit to house the laboratory. In the construction of the base laboratory unit the necessary codes of practice for construction and housing stipulated must be considered and abided by. A standard construction method and lifting, transport and placement procedures must be detailed in a standard operating procedure and the quality control practice must be adhered to ensure the longevity of the laboratories. Algorithms were developed for the selection of equipment for the laboratory based on the benefit of equipment and the dimensions of the 20 ft container. Alternative power producing, water supply and waste disposal systems were investigated with decentralized placement in mind. The modular design of the laboratory was considered and it was concluded that not all equipment is required in different deployment situations. Three laboratories will be designed for the requirements of different deployment situations. The overall premise is not to offer three laboratories, but rather for the user to choose a laboratory to me*et al*l of their needs; although the three laboratories modeled give a good basis on the minimum and maximum equipment available. The laboratories designed will also give an estimate of the cost range from the least to the most expensive which will be further evaluated in the techno-economic analysis.

2.2. METHODOLOGY

2.2.1. EQUIPMENT SELECTION

Databases Scopus, Google Scholar and PubMed were used to analyze alternative means of power production, water treatment and waste disposal in emergency situations. Technologies were selected based on the equipment selection algorithms defined in the decision rationale. The efficiency factor (Ef) of potential equipment was calculated using the maximum benefit and the space utilized. The Ef is defined by the equations 2.1. to 2.3.

2.2.2. VISUAL MODELLING

Exterior design was performed with Sketchup Pro 2015 (Trimble Navigation, California, USA). A standard 10 x 10 m land segment was drawn for the placement of the model. The models of individual equipment were obtained from the SketchUp “3D Warehouse”. The 20 ft container was drawn by GTvehicle; the water tank was drawn by Bushman; the wind turbine was drawn by DigitalBlackSmith; the PV panel array was drawn by Dangling dingle; the desk and chairs by Z.Design; the bed by Tails; the basin by TommyK; the toilet by Kohler Co. and the shower by Jarhead. All items imported were manipulated to fit the correct scale of the laboratory using the "Push/Pull" technique (U.S. Patent 6,628,279). The incinerator and internal walls were drawn and then manipulated to scale using the push/pull technique.

2.2.3. SPACE UTILIZATION OPTIMIZATION

Space utilization optimization and centre of mass distribution was performed with PackVol version 3.4.4. (Yorka Software Ltd., Italy). The dimensions and weight of equipment and container was entered into the required fields. The loading rules were set out for the orientation, vertical and longitudinal order as well as the desired weight distribution. The desired position for certain equipment was outlined and an automatic optimization was performed. The results were manually manipulated according to the design needs detailed in the results.

2.3. RESULTS AND DISCUSSION

The following section provides a brief overview of technologies selected for use in the modular laboratory system. A more detailed overview of the technical specifications is provided in Appendix A. The equipment was selected based on the equipment selection rationale algorithms developed. The modular nature of the laboratory is discussed and the equipment, 3-dimensional structure and packing details of the three 'prototype' laboratories are provided.

2.3.1. EMERGENCY MODULE POWER SUPPLY

The power supply systems for modular use in the laboratory unit were selected based on each individual systems efficiency factor. Because of different deployment situations the system was designed to be hybrid, incorporating different power generation sources. The solar, wind and biomass systems are a renewable source of energy and the battery bank and inverter selected manage and store the electricity generated.

2.3.1.2. SOLAR SYSTEM

Solar photovoltaic (PV) panels have been the answer to supplementing power systems in many disaster situations throughout the world (Higier *et al*., 2013). This is due to availability of solar energy, the portability of PV panels and low maintenance required for operation. The more available Poly-crystalline PV panels were selected over Mono-crystalline variants because of economic considerations and replacement costs. For economic viability a pallet of 25 250W Solar Panels (ReneSola Virtus II) from Sustainable Inc. was selected. The PV panels can be stacked for storage and mobility of the laboratory and upon deployment, 21 PV panels will be mounted adjacent to the container on a steel rig as shown in Fig. 2.6. The remaining 4 PV panels will aid in the repair and replacement costs of poorly functioning PV panels.

2.3.1.3. WIND SYSTEM

Wind turbine technology is well developed and understood and is used in many disaster management areas with frequent and strong wind potential (Basset *et al.*, 2015). For portability, simplicity and economic viability a 1 kW wind turbine (Kestrel e300i-1000W) from Sustainable Inc. was selected over larger, more expensive variants. The wind turbine was undersized and can be up-scale with the scaling up of laboratory space. The wind turbine kit selected comes with a charge control unit and a divert resister which relays electricity to the inverter battery bank. The system will be mounted adjacent to the container with a 4-way steel cable support system as demonstrated in Fig. 2.6.

2.3.1.4. BIOMASS SYSTEM

With the large amount of organic matter present in rural and decentralized areas in South Africa and waste disposal being a core pillar of laboratory design there is applicability for a biomass electricity-generating unit. A GEK power pellet PP 20 from Allpowerlabs Inc. was selected for electricity generation from biomass over other generators because of its small dimensions and great resource adaptability. The unit utilizes wood chips and other organics via a multi-stage gasifier, an engine and a generator controlled by a process control unit (PCU). The unit can work in isolation without fuel, with fuel and supplemented by the local energy grid, with the PCU optimizing power output. The power output will be used to operate the RO system, with any excess production diverted through the inverter to replenish the battery bank. Fig. 2.2. represents the GEK power pallet.

Figure 2.2. GEK power pallet (image from Allpowerlabs.com.)

2.3.1.5. BATTERY BANK

Due to the intermittent energy supply indicative of renewable energy systems an independent storage mechanism needs to be incorporated. The battery bank will act as a buffer by storing excess energy when the energy systems are at peak and load is small and then releasing this energy when the load is greater than the energy systems can provide. The Trojan T-105 battery will be used in a battery bank consisting of 4 or 8 batteries in parallel depending on need for the components chosen. Each battery has a 225 Ah power supply with a 6 V output. An inverter is needed to transform direct current (DC) produced by the photovoltaic (PV) panels and wind turbines to alternating current (AC) used by most laboratory equipment. The Microcare 3 kW inverter (Model No. SI-MC-3KW-INV) from Sustainable Inc. can harmonize the power output from the renewable systems to charge the battery bank. The inverter was selected because of its cost per power output. Furthermore, the pure sine wave output with high frequency pulse width modulation regulates and lowers the distortion of the power output, which will aid in the longevity of the battery bank. Additionally, the inverter is bi-directional and includes a charging outlet, allowing the battery bank to be replenished by either the biomass system in the case of the Skye-Lab or the municipal supply with the Grid-Lab.

2.3.1.1. POWER SYSTEMS MODELING

The modular design of the laboratory energy systems requires the removal and addition of components depending on the situational need. For the purpose designing the most equipment intensive Skye-Lab the following considerations were observed; due to the minimal load of the disease diagnosis, water compliance monitoring and other general equipment the load for this equipment will be drawn from the battery bank; the load intensive RO system will be powered by the biomass generator system, which contains its own control system to regulate the power output.

Following these considerations the modular design of the power system is shown in Fig. 2.3. The schematic was designed specifically as an example for the three laboratory systems modeled. Thus the schematic does not represent all the combinations of equipment that the laboratory could contain. For the purpose of the three laboratory designs the letters a, b and c and the adjacent dotted-line blocks represent each of the removable systems.

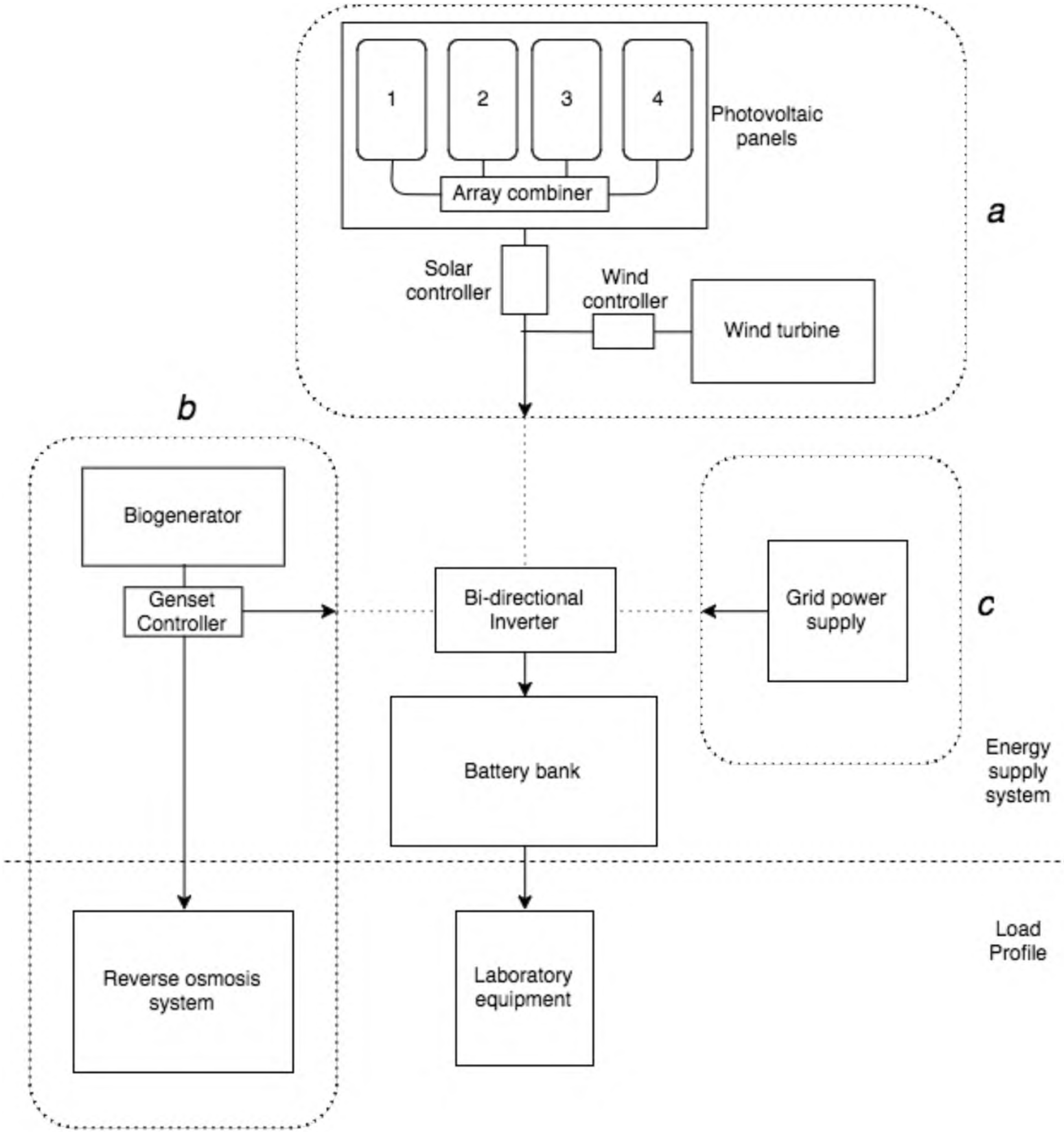

Figure 2.3. A schematic representation of the electrical control system (Drawn in draw.io)

For the purpose of an off-the-grid laboratory design systems *a* and *b* can be used to provide the necessary power output for the laboratory equipment and RO system. The load profile of the laboratory equipment and RO system is shown in Appendix A and is evaluated with the different laboratory designs in the techno-economic analysis in Chapter 3. If water treatment is not required in a particular situation and there is infrequent to no grid power supply then only system a can operate the laboratory equipment required.

In the case that a stable grid supply is available only system ***c*** will be required to run the laboratory equipment, with the inverter and battery bank acting as an emergency measure for a power outage. As mentioned previously, the schematic is not a depiction of all the combinations of equipment available in the modular design and if there is only a need for water treatment and a stable grid supply, the RO system could run independently of the biomass generator and solely of municipal power supply.

2.3.2. EMERGENCY MODULE WATER SUPPLY SYSTEM

With the modular nature of the laboratory, the premise behind the selection of the water supply system is that it could be easily added and removed depending on the deployment need. The system was selected to have the capability to produce the largest quantity of water in the smallest possible space (as this was a limitation). In the selection of the water supply system and for the purpose of creating the Skye-Lab, power usage and economic constraints were not considered.

2.3.2.1. WATER PURIFICATION SYSTEM

In the EEM system has piloted by Nerini *et al*. (2015) the RO system was undersized to prove the concept in a displaced situation. Nerini *et al*. (2015) suggested that for disaster relief placement an emergency module should be capable of providing 5000 persons per day with their water needs. The Institute of Medicine (2004) recommends an average of 3.7 L of potable water per person per day. Therefore, operating at full capacity the RO unit should be capable of producing 18 500 L of potable water per day. For simplicity of developing the prototype and the avoidance of additional costs only South African RO system suppliers were considered. Systems with similar flow rates were evaluated according to their dimensions using the efficiency factor algorithms. The 3000L/H-18 000 GPD RO system from PuriTech Inc (Fig. 2.4) had the highest efficiency factor and can produce water with a purity level of less than 40 000 PPM as required. The RO system is an optional module and its incorporation requires the use of a generator or the biomass system in off-the-grid laboratory set-ups. Connected to the grid the system can 18 000 GPD using 54 kWh.

Figure 2.4.Reverse osmosis system (image from PuriTech.com)

2.3.2.2. WATER SUPPLY SYSTEM

Water supply from nearby body will be accessed and directed to the Reverse Osmosis unit by the HT V180F Pump from Pumpsforafrica Inc. The pump is submersible and has a maximum flow rate of 100 L/min, which is adequate water supply for the RO system to process at maximum capacity. Additionally, the HT V180F has a built in filter to separate small-suspended solids in water supply bodies.

2.3.2.1. WATER STORAGE SYSTEM

In order to create a buffer between water usage and water supply from the RO system a water storage system is needed. Because of the capacity of the water supply system and the RO system the storage should have the capability to store at least one days supply at peak capacity. Adding a further buffer for redundancy a V5000 L tank from Jo-Jo Tanks Inc. will serve as the water storage system. For laboratory systems that don't need the incorporation of a RO system, the same size tank will be used, although the water will be obtained from rainwater harvesting, borehole supply or it will be delivered by an independent party. The water tank fits within the dimensions of the 20 ft container and the optimization of its packing is to follow.

2.3.3. EMERGENCY MODULE WASTE DISPOSAL

With the operation of a mobile laboratory the generation of waste, medical and human, is unavoidable. For this reason, despite the modular nature of the laboratory, the incorporation of the Gas incinerator is expected in all laboratory designs. For the purpose of the example designs the incinerator will be used to dispose of medical and human waste. In a bid to remove the necessity of the incinerator for the disposal of human waste, alternative methods of human waste disposal are investigated in a further chapter. If an adequate means to dispose of human waste is implemented then the modulation of the incinerator could be considered for the deployment of the laboratory in situations that exclude the generation of medical waste.

2.3.3.1. WASTE INCINERATOR SYSTEM

Large-scale medical waste incinerators have been used for the majority of needles, sharps and organic waste disposal in medical industry. Most mobile laboratories place their medical waste in special packaging and transport it to local hospitals or clinics that have the necessary infrastructure to dispose of it. For the purpose of a displaced mobile laboratory, quick and efficient on-site waste disposal is imperative to reduce exposure to possible pathogenic organisms. The M- L110-2 gas-fired is a commercial small medical waste incinerator sold by Cape Town based Littergon Inc. It is gas operated, consuming 3.5 kg-5 kg of LP gas per hour or per 100 kg of waste disposed with a combustion efficiency of 60 kg per hour. The emissions are well within the national regulations for medical waste incinerators stipulated in Table 2.1. The dimensions of the unit are shown in Appendix A and are shown in the scale representation of the unit in Fig. 2.5. The unit has a protective fencing around the outside and an incinerator basket that slides out for easy waste placement.

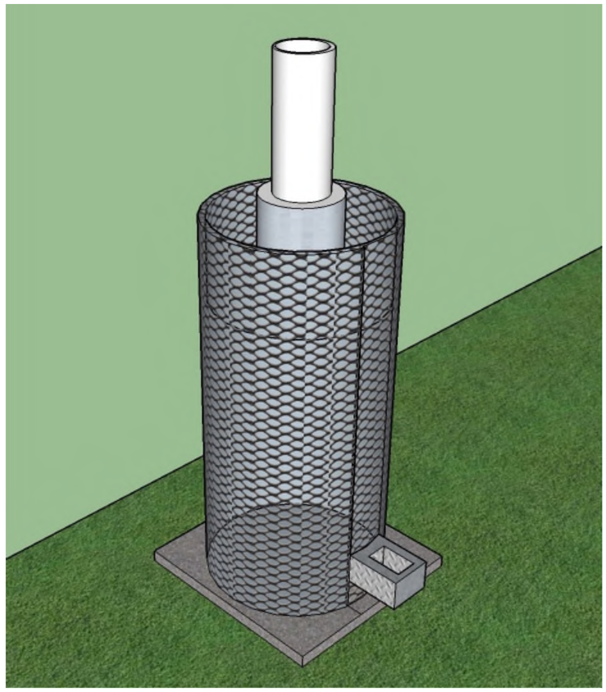

Figure 2.5. A to-scale representation of the M-L110-2 incinerator (Adapted from Littegon.co.za, drawn in SketchUp Pro 2015)

The specific model chosen has a stainless steel jacket around the outside, which allows water to be heated when connected to a supply; providing hot water to the laboratory occupant. The incinerator reaches between 800 and 1300 °C depending on environmental conditions and can incinerate human and medical waste simultaneously. In cases when a higher temperature is needed an additional 'blower' can be added to reach temperatures in excess of 1300 °C. The incinerator will be placed 3m away from the laboratory unit (Fig. 2.6.) as per South African guidelines (Table 2.1) (Rogers and Brent, 2006). For the purpose of the unit being used as a mobile laboratory, the incinerator will be used to dispose of all waste generated from the laboratory. However, due to the modular nature of the laboratory; if the incinerator is not needed for medical/infectious waste disposal an alternative to human waste only will be investigated in Chapter 5.

2.3.4. MODULAR DESIGN OF EXAMPLE LABORATORIES

Due to the modular design of the laboratory three laboratories were designed to fulfill the displacement needs of different situations. The three designs are represented according to the technology chosen in Table 2.2. Furthermore, the three-dimensional structures and the container space utilization optimization are detailed in this section.

Table 2.2. The modular equipment design of three laboratories

Technology used	Skye-Lab	Eco-Lab	Grid-Lab
Connection to local grid	✕	✕	✓
Power Pallet PP20	✓	✕	✕
Reverse Osmosis system	✓	✕	✕
Water Pump	✓	✕	✕
PV panels (x25)	✓	✓	✕
Wind turbine	✓	✓	✕
Battery Bank	✓ (4)	✓ (8)	✓ (2)
Inverter with Charger	✓	✓	✓
Water Storage tank (5000 L)	✓	✓	✓
Gas-fired incinerator	✓	✓	✓
Gas cylinder (x3)	✓	✓	✓
Accommodation (x1)	✓	✓	✓
Disease diagnosis kits	✓	✓	✓
Water compliance monitoring kits	✓	✓	✓

The Skye-lab is the most expensive laboratory, and it serves many as a proof of concept. The laboratory fulfills the need of disease diagnosis and water compliance monitoring along with the capability to providing water and power to surrounding areas. This laboratorys' primary deployment situation would be in an chronic disaster and humanitarian relief situation in which, water, power, disease diagnosis are primary concerns and there is no local surviving infrastructure.

The Eco-lab is a less expensive variation aimed at providing disease diagnosis and water compliance monitoring with only a renewable energy supply. The Eco-lab does not have a generator or RO system and thus cannot provide potable water and power to residents in the displaced location. The laboratory's primary deployment situation will be in an area where disease diagnosis and water compliance monitoring are concerns and there is an infrequent supply of power and electricity. In this case the lab will only serve as either a diagnostic clinic and/or a site for water compliance monitoring.

The Grid-lab is the most inexpensive laboratory designed and serves for a 'low-cost' variation. The laboratory also functions as a diagnostic clinic and/or a water compliance monitoring site, although it requires a grid power supply that is more frequent. This design still includes an inverter and battery bank, although a lot smaller in case of a prolonged power outage. The battery bank is charged through from the grid power supply with no alternate means of power. If the laboratory is deployed in an area with historically uninterrupted power supply, the battery bank and inverter may be forgone and the Laboratory will only run of a grid source.

All three designs have included a gas-powered incinerator to dispose of medical and human waste, if the unit is deployed in such a situation in which medical waste disposal is not needed an alternative inexpensive means for human waste disposal will be implemented; this is further explored in Chapter 5.

The three laboratories incorporate the transportation and use of a 5000 L water storage tank. This storage tank will serve different purposes depending on the function of the laboratory; if the function is to supply water to the surrounding area via the RO system the water tank can act as a buffer, storing treated water and releasing it when required. Alternatively, in the case that a buffer isn't needed or the function of the laboratory is not to provide treated water to the community then the tank can serve as a vat for rainwater harvesting. The harvested rainwater will service the needs of the laboratory occupant.

2.3.4.1. VISUAL MODELING OF THE LABORATORY

To provide a visual representation of the laboratory unit once deployed, SketchUp 2015 was used. Each three-dimensional model is designed to scale. The three laboratory designs modeled can be shown in the following two figures. Fig. 2.6. represents the external view of the Skye and Eco-Lab. The two laboratories share the same external components and therefore they do not differ in the external view.

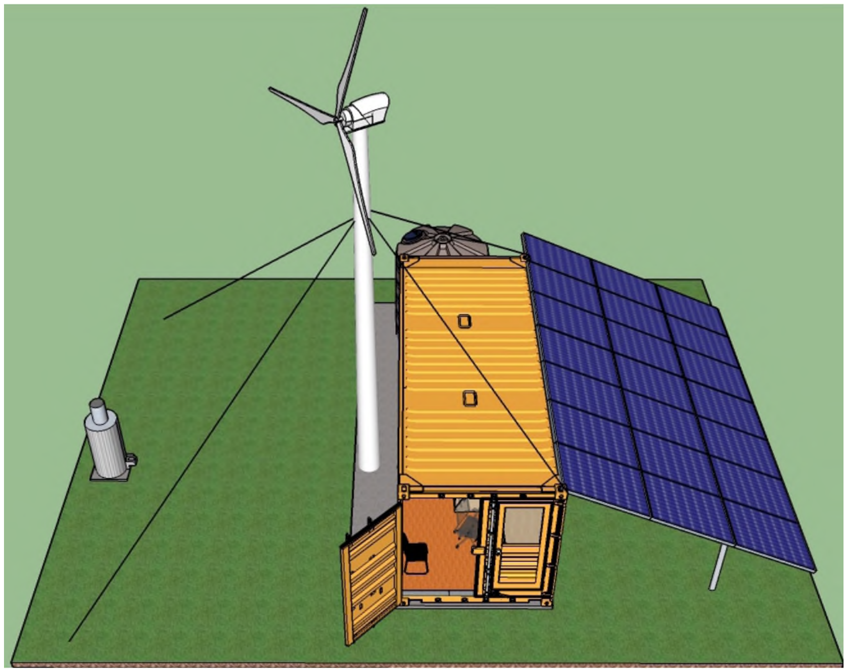

Figure 2.6. The external design of the Eco and Skye-Lab

Likewise, the Eco-lab and Grid-Lab share similar interior characteristics, as they both do not contain a generator and reverse osmosis system. The interior of all three labs is shown in Fig. 2.2. The equipment compartment featured on the right of the image is where the generator and reverse osmosis system would otherwise be housed. For all three laboratories, there is an inverter and battery bank in the equipment compartment shown and a 5000 L water tank as shown.

Figure 2.7. The Internal design of the Eco, Grid and Skye-Lab

For the purpose of correct scaling of each of the set-ups the floor plan is shown in Fig. 2.8. The plan will remain the same for all three laboratory designs except the equipment shown in the equipment compartment will differ.

Figure 2.8. The generic floor plan for the three laboratories (Drawn online at roomsketcher.co.za)

Fig. 2.7. and 2.8 represent the interior design of the laboratories in their deployment state. The multiple placements and modular design of the laboratories was taken into consideration when the interior spaces were designed. The work desk and bed shown on the left of both images fold flat against the adjacent container wall. The two chairs shown also fold flat for storage and transport, the basin and composting toilet are easily removed from their respective locations and the shower has a curtain that folds flat with the container wall. The divider between the bedroom and equipment compartment is permanently built in for the safety of the laboratory occupant. Upon deployment, access to the equipment compartment can only be achieve through the access hatch shown in Fig. 2.8.; for theft considerations the rear entry to the equipment hatch will be blocked with the water storage tank. The divider separating the office from the bedroom is less permanent and folds down from the roof upon deployment. A further analysis of the utilization of laboratory space is detailed in the following section.

2.3.4.2. CONTAINER SPACE UTILIZATION OPTIMIZATION

A key principle to take into account in the design of the mobile laboratory is mobility. The 20 ft shipping container was chosen to prove the concept of the mobile laboratory with the use of minimal space. By the design and mode of operation of a mobile laboratory, all the components needed for the situational placement are required to be packed into standard 20 ft shipping container. Along with the dimensions of the components, the mass is also important in packing the container as it ensures the containers' centre of mass is distributed evenly for minimum stress on the structure during manipulation and transport. For the purpose of optimizing the utilization of space and distribution of mass in the container the Skye-lab was used because it contains all of the equipment. Packing order and centre of mass distribution will need to be determined for each modular laboratory designed and each case will require individual approach.

The following summary and the visual representation of the pack container was performed with PackVol 2015. The following set of assumptions were taken into account when setting the limits in the simulation software:

- All dividers, flooring, and construction previously described were considered negligible in terms of weight.
- It was assumed that the equipment compartment would already be in place, so the RO, biomass, inverter and battery bank systems were loaded from the other entrance.
- The fold-down furniture (bed, desk and bedroom divider) was assume to already be mounted and it is shown in its' foldaway position.
- The external equipment was loaded last, and closet to the container door for ease of unpacking.
- All the equipment dimensions and weights included packaging.

The summary of the optimization is shown in Table 2.9. The total volume of the container was 33.02 m^3 of which all the equipment selected took up 17.67 m^3, equating to 53.51 % of the container space utilized.

Table 2.3. Summary of space utilization optimization of equipment in the container

ID	Item	Length(mm)	Width (mm)	Height (mm)	Mass (kg)	Packed/ total
1	Biomass	1200	1200	1800	791.00	1/1
2	Battery Bank	181	276	264	28.00	8/8
3	Inverter	600	400	300	15.00	1/1
4	PV panels	1640	949	40	18.50	25 / 25
5	Wind gen.	850	610	410	70.00	1/1
6	Wind blade set	1540	280	230	9.00	1/1
7	Wind tail boom	1880	280	230	15.00	1/1
8	Wind controller	350	260	180	6.50	1/1
9	Wind divert resister	390	260	150	7.50	1/1
10	RO system	1500	700	1500	132.00	1/1
11	Water pump	185	180	365	8.50	1/1
12	Water tank	1820	1820	2255	120.00	1/1
13	Incinerator	600	600	1600	80.00	1/1
14	Gas cylinders	350	350	1300	92.00	4/4
15	DD + WCM + storage	560	390	610	10.00	3/3
16	Fold-out bed	1900	900	200	15.00	1/1
17	Toilet	460	390	330	20.00	1/1
18	Basin	400	400	180	5.00	1/1
19	Fold-away chairs	400	500	200	5.00	2/2
20	Fold-up desk/counter	2000	500	20	6.00	1/1
Total (Vol. Mass, Items)		17.67 m^3			2395.00	59/59

Table 2.3. shows the number of items optimized in the space utilization process along with their respective dimensions and masses. The ID is the colour and number used to identify the items in the visual representation of the space utilization shown in Fig. 2.9. Due to close the close proximity of packing and the limitations of the three-dimensional model not all equipment is visible.

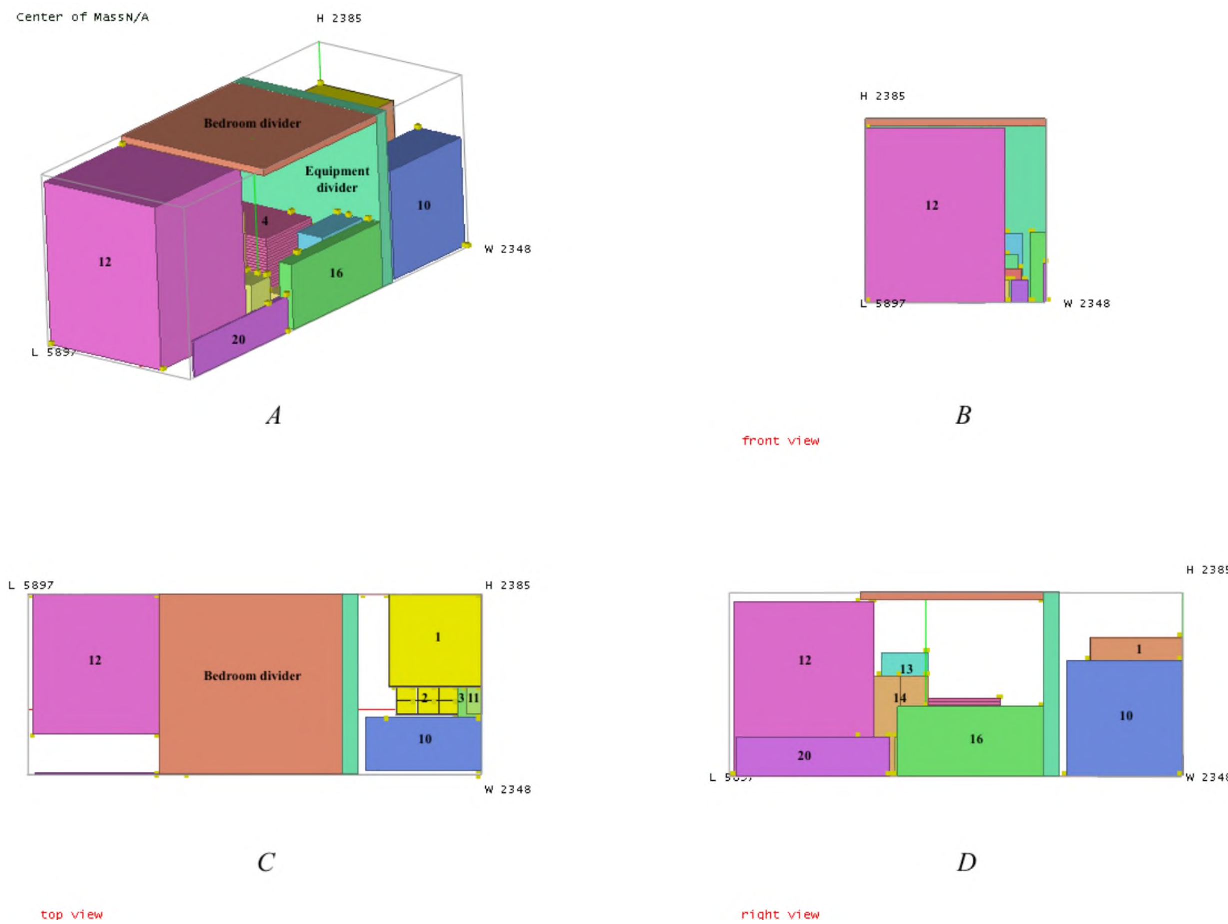

Figure 2.9. Visual representation of all the equipment in the container

A visual representation of four different views of the space utilized by the equipment in the container is shown in Fig. 2.10. View A is a three-dimensional view showing the centre bedroom compartment where not all the equipment is visible. The placement of the fold away bed and desk, 16 and 20, respectively are show clearly along with the bedroom divider on the room and the equipment divider separating the biomass system (10) and other equipment shown in View C. View B shows the front view of the container with the water storage tank (12) the last item packed because upon deployment it will be unpacked first. View C shows the top view of the laboratory, the Biomass system (1), battery bank (2), inverter (3), water pump (11) and biomass system (10) within the equipment compartment are shown here. View D shows the side view of the laboratory with the gas bottles (14) and gas incinerator (13) visible. This model serves as the dimensional layout of the optimized fully packed laboratory. However, the dimension optimization was done in a static system. It is important to not only model the dimensional space utilization but also the mass distribution. The mass distribution characteristics will serve as a basis for determining lifting, transport and placement procedures. The mass distribution model determines the magnitude and location of stresses that the container could experience; this is important in the structural stress analysis that will be perform on the prototype model. A graphical representation of the mass distribution is shown in Fig. 2.11.

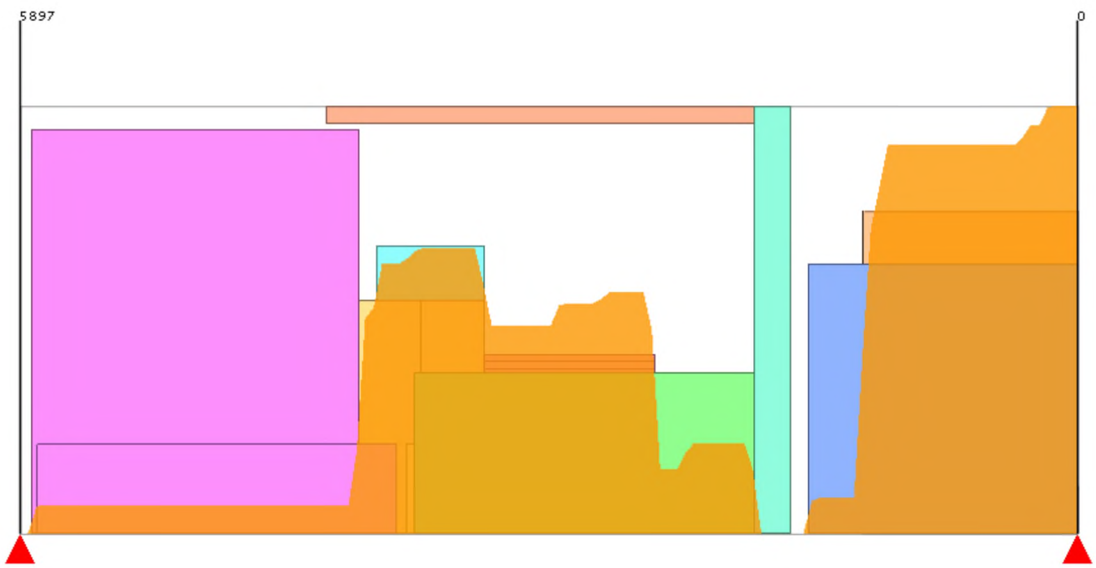

Figure 2.10. A graphical representation of the centre of mass distribution in the container

The silhouette of the equipment is shown in the background with the orange graph in the foreground representing the distribution of the total mass of 2.39 Tonnes. A large majority of the mass is distributed in the equipment compartment as expected with the remainder distributed centrally. Considering structural stability, the strongest areas are located closest to the ends on the container, which is appropriate for housing the equipment. Considering the lifting procedure, the remainder of the mass distributed centrally provide stability; the mass on the edge of the container can be counteract with the lifting procedure developed if need be. With the minimum modification to the container housing and considering the equipment mass makes up 11 % of the average maximum payload of 21.73 Tonnes, the deformation stresses on the container housing will be at a minimum. Taking this into account stress modeling can be performed on the container structure to determine if the placement of windows is structurally viable as this will create a better environment for the laboratory occupant and patients.

2.4. CONCLUSION

The successful design of the equipment selection algorithms allowed for equipment selection to be quantified within the given space. Wind, solar and biomass energy generation were selected as power producing options due to the varied availability of resources in different placement locations. The different options of power producing equipment were individually evaluated for their worth based on the efficiency factors calculated. Reverse osmosis and incinerator systems were chosen, as the means for water treatment and waste disposal respectively, based on their previous success in disaster management situations. Calculated efficiency factors were used to select systems from the RO and incinerator systems available in South Africa. Collectively, the equipment selected was within the mass and size dimensions the 20 ft container. The correct orientation and stacking of equipment was abided by, providing a relatively equal distribution of mass and therefore increased stability. As an example of modular design, three laboratories were designed incorporating different combinations of technology.

Overall, the laboratory modeled will serve as the proof of concept for the development of a prototype. Due to the modular design considerations throughout, a prototype does not require all the equipment selected and instead could implement the necessary equipment for its particular function. Up-scaling the laboratory has also been considered throughout and the equipment selection algorithms can serve as a basis to scale-up the function of a laboratory in a larger container. Ultimately, the methodology for equipment selection and simulation modeling developed throughout this chapter can serve in the selection of other equipment within different size limitations and for different purposes.

CHAPTER III: FUNCTIONS OF THE EMERGENCY MANAGEMENT MODULE

This chapter outlines the proposed function of the mobile laboratory. The previous chapter described the modular nature of the laboratory; because of the varied laboratory structure it is challenging to isolate one specific function. Because the laboratory is designed (and it is likely to be prototyped) in South Africa, the functions identified as examples for the purpose of this thesis should have applicability in South Africa. While the technology chosen in the laboratory can serve many other functions, water compliance monitoring (WCM) and disease diagnosis (DD) were identified in literature as problems pertaining to decentralized locations in South Africa. A similar approach to the equipment selection rationale (Chapter 2) was used to identify WCM and DD methodologies that were appropriate for the laboratory designed. The WCM and DD processes evaluated in literature led to the allocation of two sets of equipment draws (560 x 390 x 610) in the space utilization optimization performed in the previous chapter. Although after optimization there was space unutilized, for the purpose of portability the space requirement for WCM and DD will still remain. Novel means of microbial monitoring and disease diagnosis were investigated to serve the functions. Hydrogen Sulphide test kits were proposed for microbial monitoring and recombinase polymerase amplification (RPA) for DD. The prototype laboratory will be evaluating the implementation of RPA detection of these diseases in a field setting for the first time. It will also prove concept of using the RPA technique in a renewable energy laboratory. With the laboratory and energy systems implemented in a mobile laboratory it will significantly increase the applicability of the mobile unit to a variety of different situations.

3.1. INTRODUCTION

3.1.1. BACKGROUND

Policies implemented by the National Water Act (NWA) successfully provided 90.8% of the South African population with water within 200 m of their residences however; there is still concern with irregularity of potable water provided (Luyt *et al.*, 2012). The consumption of microbially contaminated water is directly correlated with the onset of intestinal infectious diseases (UNICEF, 2014). The total number of fatalities as a result of intestinal infectious diseases in South Africa was 14 471 in 2014, which accounted for 3.2 % of all natural deaths (Statistics South Africa, 2015c). For the 1–14 year age group, intestinal infectious diseases were the leading cause of death, accounting for 12.2 % of all natural deaths (Statistics South Africa, 2015c). This creates a need to monitor water supply for microbial contamination. According to Luyt *et al.* (2012), in rural areas, residents rely on surface water such as streams, springs and rivers for their domestic water; these water sources are not monitored for faecal coliforms and ***E.coli***; the indicator organism for faecal contamination. For the most part this water is not treated due to the unaffordability of bleach and the time and resources required for boiling (Gadgil, 1998). With the current socio-economic state of South Africa, inadequate sanitation and potable water supply are current issues that still need to be addressed. Until the cause for concern is adequately addressed there is a greater chance of infectious disease outbreaks. Such diseases can be directly related to water supply, and specifically contaminated potable water supply. Diseases that are directly related to the consumption of contaminated potable water supply are shown in Table 3.1. With one of the primary goals of the mobile laboratory being water compliance monitoring and treatment, a further function must be to detect waterborne diseases in community members. By adequately detecting the specific disease and the area in which it was contracted the laboratory can rectify the situation with testing and treatment of the water in that area as well as an informed referral of the patient to a medical clinic.

Table 3.1. Common waterborne diseases in South Africa

Name	Bacterium or Parasite	Symptoms
Chlorera	*Vibrio cholerae*	Watery diarrhea, nausea, cramps, nosebleed, rapid pulse, vomiting
Typhoid fever	*Salmonella typhii*	Fever-like symptoms, profuse sweating; diarrhea
Campylobacteriosis (Campy)	*Camplylobacter jejuni*	Produces dysentery like symptoms along with a high fever
Cryptosporidiosis ("Crypto")	*Cryptosporidium paarvum*.	Flu-like symptoms, watery diarrhea, loss of appetite, substantial loss of weight, bloating, increased gas, nausea
Giardiasis	*parasite Giardia lamblia*	Diarrhea, abdominal discomfort, bloating, and flatulence
Amoebiasis	*parasite Entamoeba histolytica*.	Abdominal discomfort, fatigue, weight loss, diarrhea, bloating, fever

(Leclerc *et al*., 2002)

The rationale behind the selection of *Giardia lamblia*, *Vibrio cholera*, *Salmonella typhii*, *Camplylobacter jejuni*, *Entamoeba histolytica* and *Cryptosporidium paarvum* for the disease diagnosis 'proof of concept' aside from their carrier, was because they are major causes of diarrheal disease and malnutrition. In addition, they all have similar physiological symptoms but for effective disease management require different treatments (Crannell *et al*., 2016).

3.1.2. WATER COMPLIANCE MONITORING

In order to address water quality in South Africa there is a great need for extensive water compliance monitoring; if a problem is unknown then it is challenging to address. Water compliance monitoring is the regular testing of water quality according to physical, chemical and microbial characteristics to determine if it is within the regulatory standards (Mackintosh and Colvin, 2003).

The current water compliance monitoring and the framework underpinning it requires review.

3.1.2.1 CURRENT WATER COMPLIANCE MONITORING

Currently the Water Service Regulation (WSR) is the legal framework which governs compliance monitoring of potable and wastewater in South Africa. In 2008, the incentive based Blue and Green drop potable and wastewater compliance certificates respectively were introduced to address ill-monitored water sources (DWA, 2009). Despite some metropolitan municipalities thriving with this new incentive based approach, many rural municipalities were not able to meet the minimum requirements as defined in Table 3.2. The lack of compliance is mainly due to lack of skills and resources, misunderstanding of the necessary standards and inadequate intervention from regulatory authorities (DWA, 2012). Atkinson (2009) suggests that the major difficulty is the ill-management of already limited resources within the rural municipalities in South Africa. With the inability of the majority of rural municipalities to comply with regulatory standards, it is a question of when and not ‘what if” a major sanitation concern and possible disease outbreak will occur. The major need for water compliance monitoring is not being met by individual rural municipalities (Medema ***et al.***, 2003). The lack of skilled labour and understanding of what is required and the decentralized location of many of these rural areas are the major difficulties to overcome. A possible solution would be to have a mobile laboratory capable of performing independent water compliance monitoring.

Table 3.2. The stipulated compliance monitoring values

Quality	Limit	Risk incurred
Faecal coliforms (CFU/100 mL)	>10	Clinical infections common, even with once-off consumption
Electrical conductivity (EC) (mS/m)	>370	Possible health risk to all individuals Increasing risk of dehydration
Total dissolved salts (TDS) (mg/L)	>2400	Possible health risk to all individuals Increasing risk of dehydration
pH	>9.5	Irritation of mucous membranes

Turbidity (NTU)	>20	Secondary health effects from possible micrbial contamination and/or pollution

(Department of Water Affairs and Forestry and Water Research Commision, 2004)

The Quality of Domestic Water Assessment guide states the minimum compliance monitoring guideline for river, dam, borehole, municipal and point of use water supply. All the necessary qualities as well as their limits are shown in Table 3.2. (Department of Water Affairs and Forestry and Water Research Commision, 2004).

3.1.2.2. MICROBIAL WATER QUALITY MONITORING FRAMEWORK

The National Microbial Monitoring Programme (NMMP) administrated by the Department of Water and Sanitation (previously the Department of Water Affairs) aims at creating a central hub for water quality data in order to improve the quality of water in South Africa (Murray *et al.*, 2004). As per the operation of the programme, water samples are collected from priority sites every fortnight and monitored in terms of turbidity, pH and concentration of ***E.coli*** (Murray *et al.*, 2004). The priority sites are determined by a NMMP coordinator and are selected on the basis of water in contact with land that may have a chance of faecal contamination; the size of the population that will come in contact with the water resource in question and the purpose that the water will be used for in that population (Sigudu *et al.*, 2014). The indicator organism is selected based on it being present when the suspected pathogen is present and absent when the pathogen is absent as well as having similar survival characteristics (Genthe and Frank, 1999). ***E. coli*** was selected as the indicator organism for faecal contamination by the NMMP because it is commonly excreted in the faeces of mammals (Medema *et al.*, 2003). Additionally, there is direct correlation between the presence of ***E.coli*** in water and the onset of intestinal infections in humans exposed to it, either through consumption or through bodily contact (Medema *et al.*, 2003). The Colilert®18 system is used to quantify the presence of ***E.coli*** in water samples for the NMMP. The system offers a shorter incubation time than others on the market (Murray *et al.*, 2004) and the desired quantification sensitivity of faecal coliforms is below the 0 CFU/100ml standard (SABS Standards Division, 2015). However, there are concerns about the reliability and cost of the Colilert®18 system. The South African Bureau of Standards identified 7.2% false positives and 12.5% false negatives for the quantification of ***E.coli*** using the Colilert®18 system (Luyt ***et al***, 2012). The cost of the Colilert®18 system is 5.63 times higher than membrane filtration methods (Sundram ***et al***, 2000) and that is not including the electricity needed to maintain an incubator at 44 °C for 18 to 24 hours. The latter part is of particular interest when power is in short supply. Additionally, with the orientation of the selection process for the sampling sites there may be important sites left out and/or new sites that emerge after the process (Sigudu ***et al.***, 2014). This identifies a need to provide water compliance monitoring on a larger scale to meet the needs of a rapidly evolving housing landscape. For this, a citizen input approach needs to be considered where the system allows for citizens to become stakeholders and add value to the process in terms of both sampling water sites in their area and reporting it for the mapping of sites to monitor and treat. In a similar approach Buytaert ***et al***. (2014) showed success in the collection of hydrological data via citizen input in Ethiopia, Nepal, Kyrgyzstan and Peru. Additionally, because of the mobile nature of the laboratory it is important to consider a monitoring process that requires as little to no energy expenditure as possible. This ensures that the load on the mobile laboratories energy systems is kept to a minimum and decreases the capacity required from the energy generating systems. The constant monitoring of water supply and subsequent treatment is necessary to minimize the risk of contracting waterborne diseases in the displaced and newly inhabited areas. Momentum is growing towards the use of citizen scientists for monitoring populations, communities and ecosystems (Zuckerberg ***et al.***, 2009). To cover large geographic areas the involvement of citizen scientists in data collection is imperative; certain drawbacks have been observed with regards to accuracy of the data collected (Dickinson ***et al.***, 2010). Some of the drawbacks include the difficulty of coordinating, training and educating larges groups of people and also maintaining participation throughout the project (Gura, 2013). In order for citizen scientists to be valuable assets adequate training for the citizens is required together with a central database for collection of information (Dickinson ***et al.***, 2010). Training should consist of one initial session highlighting the problem and the level of participation required followed by several shorter sessions throughout the project period to encourage participation (Buytaert *et al.*, 2014).

3.1.2.3. WATER QUALITY MONITORING WITH A MOBILE LABORATORY

There are numerous drawbacks with the current NMMP, one of the largest issues is the inability to accurately monitor water supply in some rural areas (Rivett *et al.*, 2009). There is a need for a monitoring framework that more adequately addresses water quality in remote and rural areas. A modified H_2S test kit that was optimized by Luyt *et al.* (2012) can provide adequate monitoring in rural areas and especially within the context of a mobile laboratory. The test kit consists of a dehydrated nutrient media within a sterile urine jar. A media has been optimized with the nutrients required for the growth of faecal indicator organisms. In the presence of the indicator bacteria $Na_2S_2O_3$ is reduced to H_2S, which reacts with Iron (also present in media) to form a black precipitate. The major advantage is that incubation occurs at room temperature (18 to 25 °C) albeit for 72 hours as opposed to 18 hours of the Colilert®18 system. This circumvents the need for an incubator to be in operation for long periods, which decreases the load on the mobile laboratories renewable energy systems. Although the incubation time is longer with the H_2S test in comparison to the Colilert®18, the test can be done in remote areas by relatively unskilled citizens which decreases logistics such as transport and refrigeration. The bacterial strains accounted for by the H_2S test kits are all of faecal origin and therefore positive tests can be a clear indication of faecal contamination (Luyt *et al*, 2009).

3.1.3. DISEASE DIAGNOSIS

When addressing water compliance monitoring it is vital to recognize it as a means for prevention of waterborne disease outbreaks. The inevitable consequence of non-compliant water is the onset of waterborne diseases; the brunt of which is faced by the poor and marginalized. It is therefore highly appropriate for a mobile laboratory that serves a water compliance monitoring function to also provide adequate means of disease diagnosis. Rapid and accurate disease diagnosis is pertinent to humanitarian relief camps and rural areas that are plagued my inadequate access to water and sanitation (Hattori *et al.*, 2016).

3.1.3.1. CURRENT DISEASE DIAGNOSIS

In South Africa, the National Health Laboratory Service (NHLS) is responsible for all diagnostic services for provincial and national health departments in South Africa (National Health Laboratory Service, 2016b). Despite the NHLS having laboratories in all nine provinces, most of them are located in urban areas. Diagnostic samples are primarily acquired in the hospital in which the laboratories reside; decentralized sample collection is performed in some rural clinics; these then require transport to a accredited diagnostic laboratory (National Health Laboratory Service, 2016b). In addition, due to the current backlog, the time taken for one diagnostic test to be performed by the NHLS, from collection to outcome is often delayed (National Health Laboratory Service, 2016a). Apart from this, many rural community members are unaware that water and improper sanitation are related to the diseases experienced (Sundareswaran *et al.*, 2015). This calls for an alternative system of disease diagnosis, preferably point-of-care rapid diagnostic tests (RDT) should be implemented in a mobile laboratory as a secondary function to water compliance monitoring. This will allow for no transport cost, quick diagnosis and also information about the whereabouts of the inadequate water supply responsible. For the example laboratory developed the primary focus is on water related disease diagnosis; due to modular nature of the laboratory and it many deployment functions, the applicability of the technology chosen to other disease diagnostics will be kept in mind.

3.1.3.2. DISEASE DIAGNOSIS IN A MOBILE LABORATORY

With the increasing need for point of care disease diagnostic, cumbersome and equipment intensive diagnostic methods are not meeting the needs. The call for inexpensive, non-energy intensive rapid diagnostic tests is required. The modern era of diagnostics has made a move towards the combination of rapid diagnostic lateral flow dipsticks and isothermal DNA amplification as an approach in point of care situations (Hattori *et al.*, 2016). The TwistAmp® DNA amplification kits produced by TwistDx Inc. (Cambridge, United Kingdom) provide simple instructions for the amplification of nucleic acid. The novelty lies in the isothermal 37 °C where the reaction takes place. The equivalent polymerase chain reaction (PCR) would require expensive and energy intensive equipment to produce similar results. The recombinase polymerase amplification (RPA) process developed by TwistDx Inc. allows for end-point of real-time detection by either, gel electrophoresis, fluorescence monitoring of lateral flow assays (TwistDx Inc., 2016). The RPA process uses recombinase enzymes that bind to single stranded DNA/RNA backbones. A copy of the nucleic acid strand is performed from the 3'-end of each complimentary strand with the aid of a polymerase. The primers that bind to each end are similar to PCR primers and aid in increasing specificity of the assay (James and Macdonald, 2015). Unlike PCR though, where varying component concentrations requires the optimization of kinetics, reaction temperature and product length; The TwistAmp® kits are optimized for fast amplification (15 minutes) with an optimum temperature of 37 °C – 42 °C and amplicon length of under 500bp (TwistDx Inc., 2016). Currently, Twist Dx offers commercially available kits for the quantification of Listeria, Red snapper, Salmonella and Campylobacter. These kits include all the probes and primers required for the amplification. However, due to the nature of the kit, it can be used to amplify a large variety of viral, bacterial and parasitic nucleic acids; with the design and use of different probes and primers. Additionally, multi-plex amplifications can be performed simultaneously. Recently, Crannel *et al*. (2015) used modified primers and probes with the TwistAmp®nfo to detect the intestinal protozoa ***Giardia, Cryptosporidium*** and ***Entamoeba*** in a multiplex assay. Furthermore, the kits have been modified to detect ***Plasmodium falciparum***, HIV-1, Group B ***Streptococci***, Shiga toxin producing ***E.coli***, foot and mouth disease virus (FMDV) and ***Ebola*** virus disease (EVD) (Faye ***et al.***, 2015; Murinda ***et al.***, 2014; Wahed ***et al.***, 2015)

The detection of ***Salmonella enterica*** can be performed using the corresponding commercial TwistAmp® kit, however it is the subspecies ***S. Typhii*** that is responsible for Typhoid fever. With the modification of primers and probes the ***S. Typhii*** could be amplified and identified with a TwistAmp® kit but for the case of specificity, an alternative corresponding ***S. Typhii*** rapid diagnostic test kit should be used. In rural areas the gold standard for Typhoid fever detection has been the Widal test however, the results are difficult to interpret in salmonella endemic locations, specifically with replicate samples of blood (Hunter *et al*., 2000). A simple and rapid alternative method has a large applicability to rural health clinics and mobile laboratories. The Life Assay Test-it™ Typhoid lateral flow immunochromatographic test strip from Life Assay (Cape Town, South Africa) identifies specific IgM antibodies associated with ***S. Typhii*** in serum and whole blood samples (Life Assay Inc., 2016). The strip consists of nitrocellulose with an immobilized antigen detection band and an anti-human IgM antibody band as the control (Gasem *et al*., 2002).

For the detection of *Vibrio cholera* the gold standard is selective isolation by stool culture (Alam *et al*., 2010). The method is time consuming, equipment intensive and requires highly trained staff. There are current alternatives that include loop-mediated isothermal amplification (Fan *et al*., 2015). The TwistDx system has a validated reputable methodology, which has been optimized for the amplification and detection of *Vibrio cholera*. An alternative rapid diagnostic test (RDT) will be used; due to the restraints of the mobile laboratory it should be simple for a laboratory operator, inexpensive and not require refrigeration. The Crystal VC™ RDT from Span Diagnostics (Surat, India) is stable between 4 °C and 30 °C and has waterproof packaging to prevent the effect of humidity on the kit. The premise of the kit is based on the detection of lipopolysaccharide with gold nano-particles. Similar to the Typhoid RDT the kit is a lateral flow immunochromatographic method except monoclonal antibodies are used and the antigen quantified is the *Vibrio cholera* serogroups O1 and O139. Substantial research has proved the Crystal VC™ RDT in field deployment situations (Harris *et al*., 2009; Kalluri *et al*., 2006; Ley *et al*., 2012).

3.1.4. PROPOSED OPERATIONAL PROCESSING

After the mobile laboratory is placed in a location the prioritization of water catchments for monitoring begins. This process involves identifying previously microbially contaminated catchments, waterborne disease prevalent areas and areas where surface water meets the residents domestic needs from the Department of Water and Sanitation databases and from surveys done in the area (DWA, 2012). A meta-analysis will then be performed with the risk assessment methodology reviewed by Luyt *et al*. (2012) to determine priority compliance monitoring sites. Along with the survey performed, an information brochure will be distributed. The brochure will contain the dangers of poor water quality and the symptoms that warrant self-presentation of an individual to the mobile laboratory. Upon self-presentation of an individual to the mobile laboratory, a standard operating procedure developed will be followed for sample collection and disease diagnosis. The patient will be required to fill in a citizen input form (Appendix B.3.) in which he/she states the source of all water used in the previous 72 hours along with an incident report form stating frequency of bowel movement over the previous 24 hours. The clinic technician will then enter an electronic case form which will link the diagnostic result to the area in which the water was consumed. The areas in which there are high prevalence of waterborne can be re-evaluated as priority catchment sites for monitoring. The procedure with the abilities of the Skye-Lab can be simply represented in Fig. 3.1.

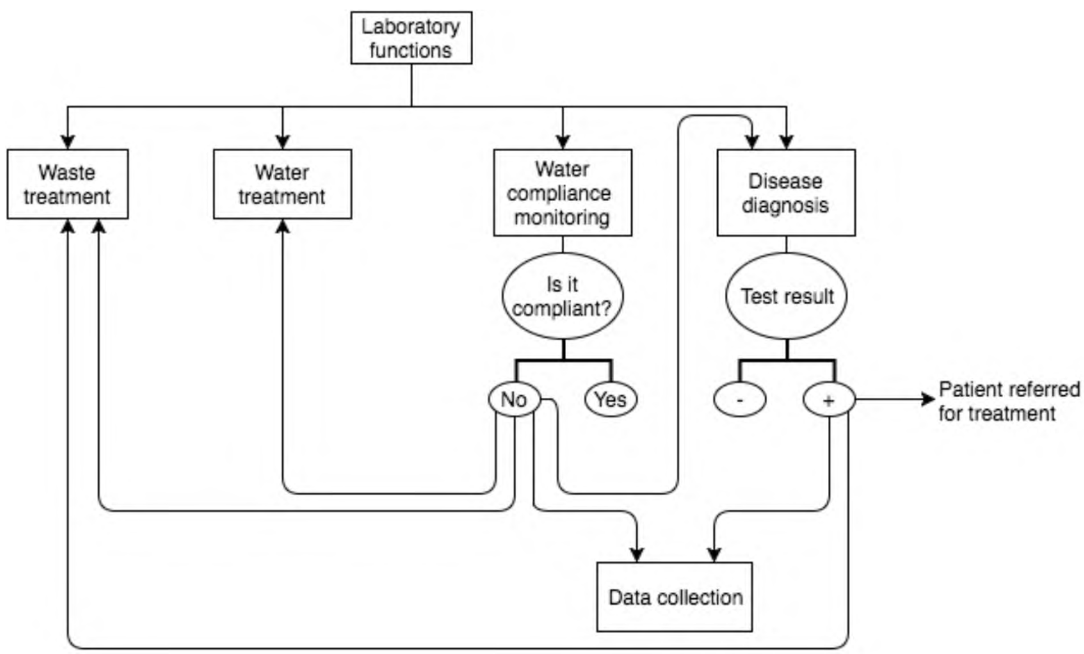

Figure 3.1. Laboratory operations processing

The Skye-Lab has the capability to treat water in a decentralized off-the-grid situation. Linking the equipment capabilities of the Skye-Lab with useful functions is an imperative step in the theoretical and prototype design. It is important to model the exact processes and the time-scale in which they will occur especially when considering the techno-economic and energy systems optimization that are detailed in the Chapter 4.

3.1.5. SUMMARY

The functions of the example laboratory were carefully considered to best compliment its already modular design and for the appropriateness of the prototype built. With the assumption that the overall laboratory structure with certain modular additions will be prototyped in South Africa, the functions were chosen to address issues pertinent to rural areas in South Africa. In addition, due to the applicability of a mobile laboratory to disaster management situations, functions were selected that would be relevant for these situations. In urban areas and non-disaster situations adequate health and sanitation is maintained by protective mechanisms in place such as, potable tap water, electricity-and therefore, heat and refrigeration (Hattori *et al*., 2016). In rural areas and similarly, disaster situations these mechanism are often compromised; leaving persons exposed to contamination and disease harboring vectors. Waterborne diseases are associated with poor quality water supply and the density of the rural or humanitarian settlements increases the likelihood of the occurrence of communicable diseases. In fact, the emergence of infectious diseases is often associated with natural disasters, and in some cases a disease outbreak, prompted by sub-standard environmental conditions, can be considered natural disasters themselves (Hattori *et al*., 2016). To illustrate this, 47 % of all deaths in South Africa are a result of AIDS and TB (Directorate: Epidemiology, Cluster: HIMME, NATIONAL DEPARTMENT OF HEALTH, 2013); higher HIV prevalence started occurring in 1990-at this point the density of informal settlements was catalyzing the spread of TB. The increased mortality was as a result of immuno-compromised HIV patients contracting TB (Mee *et al*., 2014). This demonstrates how inadequate environmental conditions can prompt a disease outbreak, and further, how the inability to address the disease outbreak can lead to the outbreak itself being classified as a disaster.

With the implementation of water compliance monitoring and waterborne disease diagnosis in decentralized and disaster locations, the concerns about inadequate water supply and its effects can be addressed simultaneously. In the example case, further water compliance monitoring sites will be determined

with the information provided from the patient (either voluntary or diagnostic). The placement of the mobile laboratory itself will create curiosity and therefore awareness of water quality and the resulting diseases.
Additionally, the technology selected for disease diagnosis has applicability in the quantification of many other communicable diseases; the premise being that the modular laboratory could be adapted to any disaster and disease scenario and provide point-of-care testing along with other pertaining needs (power and water supply).

3.2. METHODOLOGY

PROPOSED METHODOLOGIES FOR THE MOBILE LABORATORY

Databases Scopus, PubMed and Google scholar were used to determine inexpensive methods of water compliance monitoring and waterborne disease diagnosis. The methods considered to serve the laboratory functions are proposed below. A citizen engaged approach for the operation of the laboratory was developed.

3.2.1. WATER COMPLIANCE MONITORING METHODS

3.2.1.1. PHYSICAL QUALITIES

As per requirement of the Quality of Domestic Water Assessment guide the physical qualities quantified will be pH, turbidity, electrical conductivity (EC) and total dissolved solids (TDS). The measurement of each of the qualities will be performed according to the following standards: SANS 10523:2012 (pH), SANS 7888:2005 (EC and TDS) and SANS 7887:2005 (Turbidity) (SABS Standards Division, 2015). The specifications of the equipment selected to perform each protocol is shown in Appendix A. Sampling will be performed according to the standard methods (SANS 5667-2:1996) and the standard handling procedures (SANS 5667-3:2006) (SABS Standards Division, 2015).

3.2.1.2. MICROBIAL CONTAMINATION

The Hydrogen Sulphide will be prepared by an accredited laboratory in the urine jar form described by Venkobachar ***et al***. (1994) following the protocol modified by Luyt ***et al***. (2011a) (with the addition deoxycholate (0.5% w/v) (Luyt ***et al***., 2011a). The kits will be prepared with filter paper (5 cm x 10 cm) (Munktell, South Africa) folded into 2.5 cm square and placed in sterile urine jars (Spellboud Labs, Port Elizabeth, South Africa). The media will be prepared with the addition of peptone (40 g), dipotassium orthophosphate (3 g), ammonium ferric citrate (1.5 g), anhydrous sodium thiosulphate (2 g), teepol (2 mL) and L-cysteine (25 mg) to distilled water (100 mL). Mixing will be performed with the magnetic stirrer for 45 minutes. The media (1 mL) will be placed on a piece of filter paper in each urine jar and dehydrated for 24 hours at 54 °C.
Sampling of the sites will be performed in designated locations by aseptically half-filling the open urine jar with water from mid-stream of an open faucet. The kits will be closed and incubated at 18 – 25 °C (room temperature) away from light for 72 hours. Positive samples for faecal contamination will be observed with the presence of a black precipitate after the incubation period; the absence of the precipitate after the incubation period will be recorded as negative.

3.2.2. DISEASE DIAGNOSIS METHODS

3.2.2.1. SAMPLING PROCEDURE

All samples will be acquired according to the principles expressed in the Declaration of Helsinki. Informed written consent (or thumbprint) will be required from patients or their parents in the case of minors. Ethics approval will be obtained from the Medical Research Council (MRC) ethics committee as stipulated in their guidelines (Medical Research Council, 2016). Blood and stool sampling and handling will be performed according to the respective World Health Organization (WHO) guidelines (World Health Organization, 2010) (World Health Organization, 2003). Upon self-presentation of an individual to the mobile laboratory they will be requested to provide a stool sample in a disposable plastic container and blood will be sampled (5-12 ml for adults;1-12 ml for children under 14).

3.2.2.2. ISOTHERMAL RECOMBINASE POLYMERASE AMPLIFICATION

3.2.2.2.1. SINGLE-PLEX TWIST-AMP EXO FOR *Camplylobacter jejuni*

All reagents and primers are provided in the TwistAmp® exo +*Campylobacter* kit. The single-plex RPA reaction will be prepared according to the manufacturers manual (TwistDx Inc., 2016). The reaction master mix will be prepared in Eppendorf tubes with the addition of the ***Camplylobacter jejuni*** forward (10 µM) and reverse primers (10 µM), the TwistAmp® exo Probe (2.1 µM), rehydration buffer (0.6 µL), template (29.5 µL) and deionised water (13.2 µL). Mixing will be performed by vortexing followed by centrifugation. The reaction mix will be added to the reaction cell (provided) in appropriate volumes and mixed with an auto-pipette. The reaction will start with the addition of 2.5 µL of the supplied Magnesium Acetate (280 mM) vigourous mixing. The reaction cells will be placed in the Twista® at 39 °C for 20 minutes.

3.2.2.2.2. MULTI-PLEX TWIST-AMP NFO FOR *Cryptosporidium, giardia lamblia* AND *Entamoeba*

The multi-plex assay for ***Cryptosporidium Spp., Giardia lamblia Spp.*** and ***Entamoeba Spp.*** will be based on the methodology developed by Crannell ***et al***. (2015). The TwistAmp®nfo probe will be modified and the forward and reverse primers designed according to Crannel ***et al***. (2015) (Appendix B.2.). The multi-plex assay will be performed in the same way as the single-plex assay described and according to the manufacturers manual (TwistDx Inc., 2016) with the following exceptions; the master mix will consist of rehydration buffer (29.5 µL), deionized water (7-11 µL), ***Giardia*** forward and reverse primers (0.74 µL each) and probe (0.28 µL); ***Entamoeba*** forward and reverse primers (0.81 µL each) and probe (0.38 µL); ***Cryptosporidium*** forward and reverse primers (0.53 µL each) and probe (0.2 µL). All primers and probes will be 10 µM concentration. The volumes of master mix will be added to the reaction cell and the reaction performed as previously described.

3.2.2.2.3. VISUALIZATION OF AMPLICONS

The reaction cells will be removed from the Twista® and 5 µL will be made up to 100 µL using tris-buffered saline solution (0.05 % tween20, 25 mM tris, 150 mM NaCl). The Milenia HybriDetect 1 lateral flow strips from TwistDx will be placed in the solution (conjugate end down) for 10 minutes. Following which the results will be recorded in the case report form (CRF).

3.2.2.3. RAPID DIAGNOSTIC TESTS

3.2.2.3.1. CRYSTAL VC DIPSTICK FOR *Vibrio cholerae*

The Crystal VC® dipstick rapid test from Span Diagnostics, Surat, India wil be stored at room temperature. The test will be performed according to the manufacturers manual provided. Stool will be collected from a patient in a disposable container according to the approved standard operating procedure, following which 200 µL will be added to the disposable tubes provided. The dipstick will be inserted into the tube and left for 20 minutes. After the reaction has taken place the visual appearance of two band will indicate a positive result for *V. cholerae* and the occurence of one a negative result. The lack of any bands will indicate a procedural error. The results will be recorded in the case report form (CRF).

3.2.2.3.2. LIFE ASSAY TEST-IT FOR *S. Enterica typhii*

The Life Assay Test-it™ Typhoid IgM (Life Assay Diagnostics (Pty), Cape Town, South Africa) will be used to detect for *S. enterica Typhii*. The test will be performed according to the manual provided on the blood culture collected from patients according to the standard operating procedure. The assay will be performed with the incubation of the dipstick in concentrated blood or an isolated serum sample at room temperature for 20 minutes. The dipstick will then be thoroughly washed with water, dried and observed for staining. The intensity of the band will be graded by the clinic technician with reference to a strip provided; no band is considered negative and 1 to 4 are positive increasing in the intensity of the band. The results will be recorded in the case report form (CRF).

3.2.3. OPERARTIONAL PROCCESSING

Upon presentation of an individual to the laboratory the choice of diagnostic test to run will be evaluated based on the symptoms experience as shown in Table 3.1. The patient will also be asked to fill in a citizen input form shown in Appendix B.3, this will determine the individuals area of residence and the locations in which he has been exposed to water. Ethics approval will be sought from the National Health Research Ethics Council (NHREC) for the collection and use of all citizen input data (NHREC, 2016). The input form is optional and filling in the form will act as consent to use the information provided. Once submitted the anonymized information will be logged along with the bacterium or parasite present in that individual; this area will be noted as a priority zone for water compliance monitoring and samples will be tested from the identified water source and based on these results treated water will be supplied to residents in that area.

3.3. RESULTS AND DISCUSSION

THEORETICAL FUNCTIONS

The following section details a brief comparison between methodologies selected and the standard procedures currently in practice. The equipment necessary and specifications are shown in Appendix A.

3.3.1. WATER COMPLIANCE MONITORING

3.3.1.1. FAECAL CONTAMINATION IN WATER

When compared to the NMMP's Colilert®18 system the H_2S test kit correctly identified 84 % of faecally contaminated samples as opposed to 75 % (Chuang *et al.*, 2011). The Colilert®18 system had 19 % false negatives compared to 6 % with the H_2S kit while the false positives was greater in the H_2S kit with 10 % compared to the Colilert®18 system with 6 % (Chuang *et al.*, 2011). Considering the monitoring of potable water, it is preferable to have the least amount of false negative tests as possible; if faecally contaminated water is consumed it may cause a waterborne disease outbreak, in this case the H_2S kit is preferable with only 6 % compared to the 19 % Colilert®18 system. False positives are not as important indicators of a potable water quality assurance test as they lead to further scrutiny and testing of the water source and will stop the potable use of the water source until it is deemed fit for consumption.

3.3.2. DISEASE DIAGNOSIS

3.3.2.1 CHOLERA DIAGNOSIS

The gold standard for laboratory diagnosis of Cholera in a patient is isolating ***Vibrio cholerae*** serogroup O1 and/or O139 from a stool sample by culture. This is done using the Cary-Blair media thiosulfate citrate bile salts agar for selective isolation . However, in a mobile laboratory with limited equipment the rapid diagnostic dipstick can serve as an alternative. The Crystal VC® dipstick rapid test from Span Diagnostics, Surat, India is a reliable alternative. The dipstick showed a sensitivity of 93.1 % and specificity of 49.2 % when compared to the gold standard (Ley ***et al.***, 2012).

3.3.2.2. TYPHOID FEVER DIAGNOSIS

For the laboratory diagnosis of Typhoid fever, blood and stool cultures on selective media and Polymerase Chain reaction (PCR) determination remain the gold standard for ***Salmonella typhii*** confirmation. However, this process takes between 7 to 12 days and requires a well equipped laboratory. In the case of rural settings and in a mobile laboratory where equipment is limited the Life Assay Test-it™ Typhoid IgM from Life Assay Diagnostics (Pty), Cape Town, South Africa can serve as an alternative. The rapid diagnostic kit detects IgM antibodies for the O antigen of ***S. enterica Typhii*** and provides a result in 15 minutes. Maude and colleagues found the Life Assay test to have a sensitive of 86.7 % and a specificity of 64.8% when compared to the gold standard (Maude ***et al.***, 2015).

3.3.2.3. CAMPYLOBACTERIOSIS DIAGNOSIS

The gold standard for the identification of ***Camplylobacter jejuni***, the bacteria responsible for Campylobacteriosis is by culture of a stool sample on the selective brucella agar. This method often has limited sensitivity and is time consuming, labour and equipment intensive (Harrington ***et al.***, 2015). PCR techniques are expensive and require energy intensive equipment. And alternative is the recombinase polymerase amplification (RPA) developed by TwistDx, Cambridge, United Kingdom. Unlike PCR this process provides rapid amplification of DNA or RNA segments at one temperature. Possibly, due to the commercialization of the Campylobacter methodology by TwistDx Inc, the research and development of the test is not available in the public domain. However, Dong ***et al.*** (2014) performed a comparison between PCR and an equivalent isothermal amplification technique for the Campylobacter hipO gene. Dong ***et al.*** (2014) found the isothermal technique to be 10 times more sensitive than the PCR assay with a detection limit of 100 fg/pl. It was also found that the isothermal technique was less sensitive than PCR to potential inhibitors with 84.4 % sensitivity compared to the 35.5 % of PCR (Dong ***et al.***, 2014).

3.3.2.4. CRYPTOSPORIDIOSIS, GIARDIASIS AND AMOEBIASIS DIAGNOSIS

Culture techniques in combination with PCR is currently the gold standard for the detection of ***Cryptosporidium Spp., Giardia lamblia Spp.*** and ***Entamoeba Spp.*** (Crannell ***et al.***, 2016). The limitations of PCR with regard to a mobile laboratory system have been previously discussed. The RPA method used for the identification of ***Camplylobacter jejuni*** has several other applications. This assay in combination with a multiplex lateral flow system also from TwistDx has the capability to quantify all three organisms in real time (Crannell ***et al.***, 2016). The protocol developed by Crannell and colleagues is a novel approach and gives quick results to diagnose common organisms responsible for diarrheal illness. The specificity and sensitivity of the RPA results is yet to be compared to the PCR equivalent.

3.4. CONCLUSION

The purpose of this chapter was to select the appropriate technologies to fulfill the expected functions of the mobile laboratory. The functions were first selected according to the issues outlined in the review of literature and the premise behind the prototype design. The modular nature of the laboratory and its many applications were considered in the selection of functions as described in the introduction. All of the tests were chosen for simplicity and rapid diagnosis for a means to map the outbreak zones of specific diseases as a means for an early response to inadequate water supply. Each patient receiving preliminary diagnosis will therefore be referred to the nearest clinic, hospital capable of treating the patient accordingly.

Water compliance monitoring will be performed with the standard physical analysis method described however the H_2S test will be used as an inexpensive alternative for the microbial analysis. Novel methods will be adopted for waterborne disease diagnosis function. For the quantification of Cholera and Typhoid fever the respective lateral flow immunochromatographic test will be used as inexpensive rapid alternatives to quantification by culture. With regard to Campylobacteriosis, Cryptosporidiosis, Giardiasis and Amoebiasis quantification, recombinase polymerase amplification (RPA) will be combined with immunochromatographic lateral flow assays for detection. The RPA technique is a recent, novel technique that is perfect for implementation mobile laboratories (Crannell *et al.*, 2016). The prototype laboratory will be evaluating the implementation of RPA detection of these diseases in a field setting for the first time. It will also prove concept of using the RPA technique in a renewable energy laboratory. In addition as the technology develops Cholera and Typhoid fever quantification could also be quantified with the RPA system. In fact the technology makes it possible to rapidly and inexpensively diagnose many other communicable. James and Macdonald describe the detection of ***Plasmodium falciparum***, HIV-1, Group B Streptococci, Shiga toxin producing ***E.coli***, foot and mouth disease virus (FMDV) and Ebola virus disease (EVD) amongst other less prevalent diseases (James and Macdonald, 2015). This makes the TwistDx system imperative in a mobile laboratory not only for waterborne disease diagnosis but also for epidemic outbreak situations.

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CHAPTER IV: SIMULATION, OPTIMIZATION AND ECONOMIC ANALYSIS OF LABORATORIES

The following chapter serves to evaluate all the design elements of a mobile laboratory in terms of economic feasibility. In order to achieve this the capital cost of the project along with the cash flow throughout the projects' lifespan was investigated. To gauge the effectiveness of the laboratory developed, a comparison of three laboratory systems designed for different situations was performed. Techno-economic analysis was performed with the optimized systems from HOMER Pro (HOMER Energy, USA) with the Net Present Cost (NPC) estimation and a sensitivity analysis on the effect of Diesel, battery life and electricity rates on each of the laboratories. The cost benefit analysis was performed by quantifying the benefits of each of the laboratories placement in monetary terms with aid of the Social Return on Investment (SROI) methodology. Stakeholders were selected as beneficiaries and their return was calculated in terms of a 'cost to benefit' ratio with aid of financial proxies from databases and developed for the project (Global Value Exchange, 2016). The cost-benefit ratio states the value of return in ZAR (or other currency equivalent) for every 1 ZAR invested as capital. The novelty of this chapter exists in the combination of techno-economic optimization of a mobile laboratory with the SROI methodology in a developing country.

4.1. INTRODUCTION

4.1.1. BACKGROUND

A tri-fold increase in natural disasters was observed from the years 2000 through 2009 compared to 1980 through 1989 (Leaning and Guha-Sapir, 2013); this together with the ever-increasing shift of momentum away from fossil fuels towards renewable energy (Khan and Iqbal, 2005); there is a need to evaluate stand-alone energy systems as a means for disaster management. Additionally, stand-alone energy systems may also serve as a power supply to decentralized settings that do not have access to municipal power grid (Khan and Iqbal, 2005). There is currently a significant paradigm shift towards the use of renewable energy for these stand-alone systems but there are still systems, particularly in humanitarian relief situations, utilizing diesel generators for their power supply (Sundareswaran *et al.*, 2015). In designing a stand-alone system for a mobile laboratory, increasing the capacity of PV panels, the use of wind and supplementation of biomass power generation should drastically decrease fossil fuel reliance, decrease environmental impact and lessen operations costs (Ashok, 2007). With the ongoing development of new energy producing components, the understanding and optimization of these components in systems is imperative (Khan and Iqbal, 2005). Specifically with regards to modular laboratory design where the implementation of the unit is largely situation dependent, Santarelli, (2004) found that the optimized solution is situation specific and the results depended largely on meteorological resources and load profile. Considering this and the modular design of the laboratory it is challenging to account for all possible situational placements and all laboratory load profiles; for this reason, for the purpose of this chapter, three different laboratory designs outlined in previous chapters will be individually simulated and optimized and then compared accordingly. Each system will be evaluated with the simulation and optimization tool HOMER Pro v3.6.1. HOMER (Hybrid optimization of multiple energy resources, California, USA), which contains several energy producing components each with customizable parameters. In performing the analysis, information regarding resources, electric load, economic constraints and equipment cost (initial and maintenance) amongst others was used. The tool runs an algorithm that lists each possible combination of the components chosen and analyses the cost and electric output of each system with a focus on maximizing renewable energy components and minimizing fossil fuel based sources to provide a set load (HOMER Energy, 2016).

Along with the optimized economic considerations from the Techno-economic analysis (TEA) of each laboratory a comparison with current systems in place providing similar functions will be performed. For the laboratory developed for the functions of water compliance monitoring and disease diagnosis a comparison to the estimated price of the current processes. This comparison is relatively simple, although because of the novel concept of the laboratory and the multiple functions it may perform it is difficult to provide a comparable system that is all encompassing. For example, the NHLS may be used to compare the cost of DD per patient by taking into account both the cost to them as well as the transport cost estimations for self-presentation of the patient. This does not take into account all the estimated benefits of a mobile laboratory; for example, the number of patients is expected to increase due to the close proximity and increased awareness associated with its' placement. This is only by comparison of DD; if the laboratory were to provide potable water, power supply and water compliance monitoring the benefits are multi-fold and therefore comparison by one particular function becomes redundant (Millar and Hall, 2013). For this purpose the cost benefit analysis will be performed with the cost estimations and sensitivity analysis performed by HOMER, but the qualitative Social Return on Investment (SROI) methodology will be adapted to fully represent the benefits in monetary terms (Millar and Hall, 2013). The SROI is a technique used to comprehend and quantify social, environmental and economic value of an organization or product (Aeron-Thomas *et al.*, 2004).

Holistically, the main primary elements that need to be taken into account are the cost of preparing the container needs, the cost of equipment and operations and management costs, the excess load and water produced (if relevant) and the social and environmental benefit (if relevant).

4.1.2. COST-BENEFIT ANALYSIS OF PROTOTYPE

In order to evaluate the technologies selected to fulfill the necessary operation and function of the laboratory in terms of economic feasibility a techno-economic analysis is required. The key principle behind a TEA is providing a detailed cost-benefit analysis (Lauer, 2008). In order to perform the TEA the following objectives need to be performed (Lauer, 2008).

- Evaluation of the capital cost of the project;
- Determine the operations and management cost of the project time period;
- Comparison and trade-off between output and cost of equipment providing the same function.

The power producing technologies chosen were chosen according to needs provision and then in accordance with their efficiency factors; where first the dimensions of the components and performance were considered. By this methodology cost was only considered when there was an option between two or more components with similar dimensions and the same power output.

A cost-benefit analysis is required to determine the economic benefit of the project. Static cost-benefit assessment is used for most product production analyses because it takes place over one year and excludes interest and inflation rate, which make its relatively simple. Imprecise results and underestimation of investment related cost occurs frequently. The static cost-benefit model is represented by the following formula [4.1.] (Hutton *et al.*, 2007).

$$\mathbf{r = B_{total} - C_{total}} \qquad \textbf{[4.1]}$$

Where r is the ratio of benefits (B) to costs (C) represent benefit and cost. The cost calculation algorithms in HOMER pro accounts for capital cost and operating and management costs and gives Annualized and Net Present Cost (NPC). The benefit algorithm only accounts for sell back revenue from excess power production and therefore a more complex analysis of benefit is required.

The overall benefit of a mobile laboratory is difficult to quantify and can only accurately be calculated upon implementation of a prototype laboratory. The direct benefit to the community once the prototype is in place will be defined by potable water provided (W_p) in L per day to the community, the number of patients diagnosed with a water-borne disease (D_d), the quantity of sites monitored for compliance (S_m) and the power provided (P_p) in W which can be represented by:

$$\mathbf{B_{total} = W_p + D_d + S_m + P_p} \quad \textbf{[4.2]}$$

Considering the availability of diagnostic services is what would prompt the implementation of the mobile laboratory, initially the number of diagnostic cases with the laboratory in place should increase; this is due to diseased individuals not having the avenue for diagnosis that the laboratory provides. From the operation of the laboratory and the citizen input approach the frequency of waterborne disease diagnosis should decrease over time; this is due to the public awareness of contaminated water sources and a government-based intervention to rectify the inferior water quality.

4.1.3. COST ASSESSMENT

4.1.3.1. INVESTMENT RELATED COST

4.1.3.1.1. COST OF CONTAINER CONSTRUCTION

Before the container can serve as a laboratory and housing unit the process of retro-fitting the inside and outside of the container with the necessary structural adjustments needs to take place. The cost of the container and the modifications were based on quotes from the biggest South African container retailers namely, Fabricated Steel Manufacturing (Johannesburg); Spazatainer (Cape Town); Containerworld (Johannesburg) and Big Box Containers (Cape Town). In determining the price of modifications the following assumptions were made:

- No raw materials transport costs were included in the calculations;
- Labour costs were included in the total price for each section;
- The cost data for the duration of the project was based on the initial quotations;
- The property cost of deployment area was not considered;
- Water and electricity rates for construction were not considered.

The cost estimate to retrofit one 20 ft container for the use of a mobile laboratory was calculated based on an average of the quotes obtained from the different contractors previously mentioned. The reason the mean cost from four retailers was used is to provide a more accurate cost estimate and to eliminate the impact of economies of scale. The mean cost for each of the processes needed is shown in Fig. 3.1.

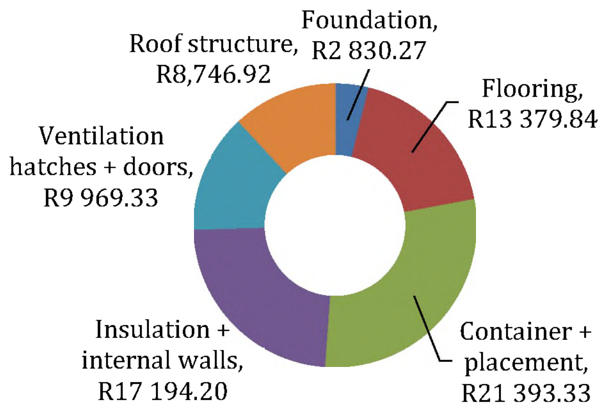


Figure 4.1. Breakdown of the mean costs associated with building the basic laboratory structure

The average total cost therefore is 73513.89 ZAR, which is 5277.37 ZAR per square metre (m^2).

4.1.3.1.2. COST OF EQUIPMENT

A key step in determining the cost-benefit analysis is quantifying the total capital cost of all the equipment (Lauer, 2008). A full breakdown of capital required for the new purchase of all the equipment required for the mobile laboratory to fulfill its function is shown in Appendix A. Below in Fig. 4.2. is the proposed capital cost comparison between the three laboratory systems. The cost of container construction was standard for all three laboratories and therefore it was excluded in the equipment capital cost. The exclusion of this standard cost allowed for the comparison of the cost of equipment for the three laboratories. The standard container construction cost was used in the calculation of the final cost of the project. It must be noted that the determining the capital cost is the first step in the techno-economic analysis; these values will be used to perform simulation and optimization and with the specifications of the equipment used, the operations and management cost.

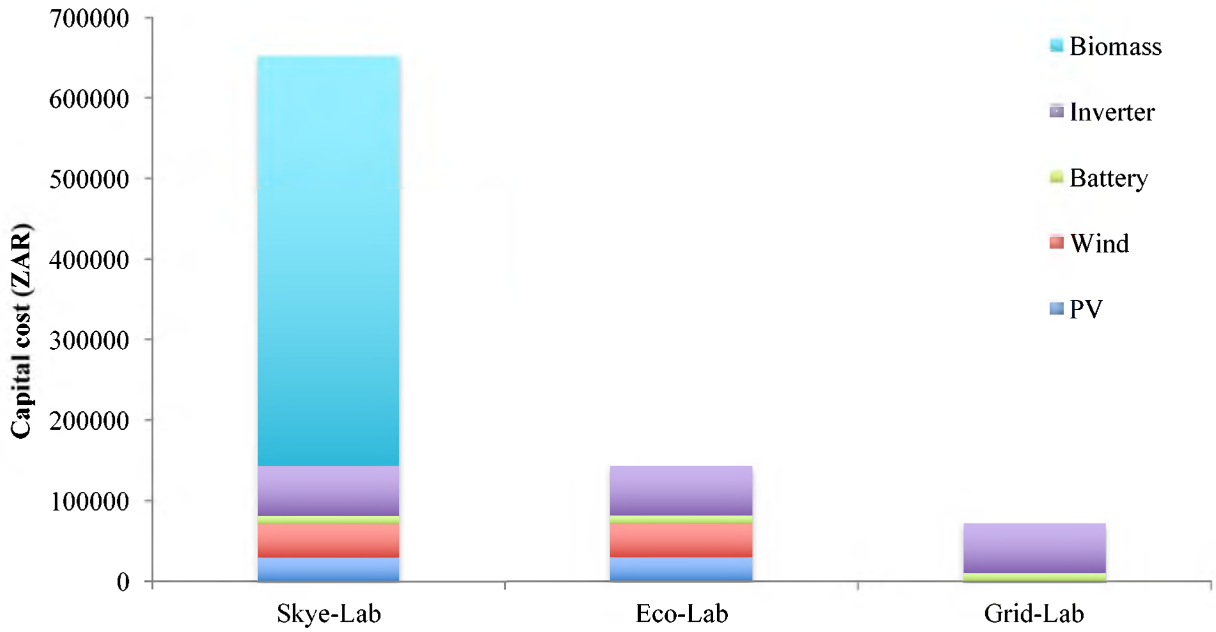


Figure 4.2. Proposed capital cost of the power producing technology for the three laboratories (Appendix A)

4.1.3.2. OPERATION RELATED COST

4.1.3.2.1. ENERGY SYSTEMS COST

In the simulation performed in HOMER the total cost of the equipment is stipulated, the percentage inflation (7 %) is taken into account and the price of diesel (10 ZAR/L) for the simulated project lifetime. The NPC includes the operation and management of the equipment in the laboratory. A sensitivity analysis of these parameters will be performed to determine their ultimate effect on the net total cost of the energy systems. A sensitivity analysis aims at determining the effect of uncertain variables on the outcome of a given system (Saltelli, 2002).

4.1.3.2.2. LABOUR COST

For the cost of labour, one laboratory operator was considered to work 7 hours a day six days a week with a total of 42 hours per week, in accordance with the operational needs of the laboratory and the Basic Conditions for Employment

Act (Department of Labour, 2016). For the determining the pay-scale, the laboratory operator was considered to have had vocational training and/or have a diploma certification as a laboratory technician and the laboratory placement was considered in Area C- peri-urban/rural areas. Based on these variable the minimum wage should be in excess of 26.16 ZAR per hour (My Wage, 2016) (Department of Labour, 2016). For the purpose of determining the rate per hour of the laboratory operator the benefits of board and lodging were not taken into account and instead the value of 5000 ZAR per month was decided on; equating to 29.76 ZAR per hour. A nominal inflation rate of 7 % per annum was applied to the operators' salary for the duration of the project of 20 years.

4.1.3.2.3. LABORATORY EQUIPMENT COST

The cost of the laboratory equipment was calculated with the values in Appendix A. For the RO system the replacement of the membrane was estimated to take place once annually. The gas tanks responsible for the operating of the cylinder were estimated to require refilling 29 times throughout the project duration based on the estimated LP gas consumption of 5 kg per week. For the purpose of disease diagnosis and water compliance monitoring the cost of a full diagnostic array was 251 ZAR per person and 30 ZAR per site (Appendix A). The enteric disease research unit (EDRU) a group part of the National Institute for Communicable Diseases currently receives 4000 specimens for diagnosis nationwide (NICD, 2015). Based on placement the number of patients could vary substantially. For the purpose of the analysis the laboratory will be expected to perform the full diagnosis spectrum on 4 patients per week equating to 212 per year, which is 5 % of the current diagnostics by EDRU (National Health Laboratory Service, 2016a). The compliance of 5 sites per month will be monitored, with ongoing prioritization occurring according to the methodology described in Chapter 3.

4.1.4. BENEFIT ANALYSIS

The SROI analysis described in Chapter 1 was selected as the most appropriate methodology for quantifying the benefits of the laboratory. The SROI guide developed by Social Value UK was selected as the most appropriate methodology to follow based on its previous implementation in healthcare and rural settings and because it is under a creative commons license that allows for academic use (Social Value UK, 2016a). The SROI guide identifies the adaption of project indicators to align with readily available financial proxies as a risk for inaccuracies (Social Value UK, 2016a). Several SROI analysis software tools were reviewed; majority were inaccessible in the public domain without a 'SROI Accreditation'. The SROI accreditation is an intensive course designed to equip an individual with the necessary skills and toolkit to interpret and develop social values in the databases and compile information into SROI reports. The accreditation comes with the perks of access to all of the current databases and a network of other SROI practitioners (Social Value UK, 2016b). The databases contain comprehensive store of social value financial proxies and allow for the calculation of the total benefit of a given project in monetary terms.

In an attempt to find relevant financial proxies the Global Value Exchange; Social Return on Investment (SROI) Network; Centre for Social Impact Bonds; HACT Social Value Bank and the SROI Canada Network Financial Proxy Databases were consulted (Global Value Exchange, 2016; HACT, 2016; Office of the Cabinet, UK., 2016; SROI Canada, 2016). The HACT database gave benefit cost of being debt free and having financial comfort for the individual; quantified as 36 249.15 and 202 979.54 ZAR per year respectively. The benefit of having good overall health was calculated to be worth 458 406.09 ZAR per person per year (HACT, 2016). The more comprehensive Unit cost database (v1.4) as part of the Social Impact Bond Toolkit stated the cost of truancy on state to be 23 852.37 ZAR per person per year; where truancy is defined as missing at least five weeks of school per year (Heady *et al.*, 2007). Similarly, the foregone income of an individual having not completed high school was calculated to be 54 766.46 ZAR per year as shown in the SROI financial proxy database of Canada (Hankivsky, 2008; SROI Canada, 2016). The values mentioned act as a source for comparison for the values calculated in this chapter.

For the purpose of this project, the indicators mentioned were used as infrequently as possible and unique financial proxies were developed to try and quantify the outcomes each stakeholder receives from the implementation of the project. The benefit of implementing a laboratory in a delocalized area is difficult to quantify in monetary terms.

4.1.4.1. LABORATORY FUNCTIONS

Before the identification of stakeholders the exact functions of the laboratories and the intended changes that the placement of a laboratory would catalyze were identified. As a standard, and to form the basis for the identification of stakeholders, disease diagnosis and water compliance monitoring were isolated as the primary function of all three laboratories. The intended changes that the different stakeholders selected could experience as a result of these functions were listed. The changes to existing stakeholders with the additional functions of water treatment (Grid- and Skye-Lab) and electricity production (Skye-Lab) were then selected; for the simplicity of cost calculations and to avoid overestimating benefits, additional stakeholders were not considered for these functions.

4.1.4.2. SELECTION OF STAKEHOLDERS

Providing disease diagnosis, water compliance monitoring, potable water and electricity to a decentralized population involves multiple stakeholders all with different levels of invested interest. The purpose of this SROI analysis is to gather an estimate of overall benefit of the project to the community. The benefit to each stakeholder does not need to be quantified individually. By grouping multiple stakeholders together there is a decreased risk of over-estimating the benefit making the analysis more accurate (Global Value Exchange, 2016). For the purpose of this analysis the stakeholders identified to benefit from the intended changes were the rural/disaster population surrounding the placement of the laboratory and 'the government'. The government is a stakeholder group that consists of all the governmental departments, municipalities and provinces that received benefit for the intended change the laboratory is expected to exert.

4.1.4.3. EXPECTED CHANGES

The rural placement of the laboratory is expected to decrease travel cost and time of individual requiring diagnosis. There is a large body of evidence suggesting that distance has become a barrier to primary health care access in South Africa (Tanser *et al*. 2006). Cooke *et al*. (2010) reported that even with the provision of anti-retroviral therapy for AIDS treatment individuals greater than 5 kilometers from the access point were half as likely to collect their medication as those closer (Cooke *et al.*, 2010). Some of the reasons for the impedence of distance on clinic attendance were travel time and cost. Tanser *et al.* (2006) reported an average of 73.6 minutes travel time on a survey performed in Gauteng, South Africa, and found increased travel time to have a direct effect on clinic attendance. McClaren *et al.* (2012) ascertained the effect of Euclidean distance on clinic attendance and linked this to household income; showing that the cost of travel was an impedance factor on clinic attendance. However, no current literature identifies a monetary value for cost of travel in a decentralized area in developing countries. The effect of distance from clinic isn't limited to the individual requiring treatment, poor clinic attendance, specifically with regard to communicable disease diagnosis ultimately costs the South African economy as well; it is attributable to increase fatalities and decreased work efficiency. The costs that should be considered is the amount an citizen in a rural areas would have to pay for travel to a clinic providing disease diagnosis and the costs of the fatalities and decrease work efficiency cause by intestinal diseases. Additionally, the cost of establishing an equivalent solution should be analyzed.

A large benefit of the laboratory placement and the functions of the laboratory is the decreased travel time to receive intestinal disease diagnosis and more importantly an increase in labour productivity prompted by the decrease in work absenteeism associated with intestinal diseases.

The increasing WCM and production of electricity and potable water is expected to directly increase access to sanitation. The DD function is expected to directly affect the number of fatalities and the mobile laboratory placement is expected to increase awareness of sanitation concerns and indirectly address sanitation. The increased awareness will aid with the education in safe sanitary practices in the surrounding communities thereby increasing sanitation. At the end of the MDG South Africa fell 23 % short of meeting the sanitation goals; the estimated benefits of meeting these goals was calculated to be 15.5 billion ZAR, with convenience time savings accounting for 63 %, productivity gains accounting for 28 % and cost of health care 9 % (WHO, 2007).

4.2. METHODOLOGY

For comparative purposes all values were shown in ZAR, all conversions were performed with the exchange rate of 1 ZAR= 22.62 GBP and 1 ZAR= 15.63 USD.

4.2.1. SYSTEMS SIMULATION

The hybrid system simulation and optimization of the designed energy systems was performed using Hybrid optimization of multiple energy resources (HOMER) computational simulation Tool (HOMER Pro v 3.6.1) (HOMER Energy, 2016). The performance of the energy systems was modeled in Grahamstown, South Africa (33°18.9'S, 26°29.7'E). The 21 PV panels had combined nominal capacity of 5.25 kW (32.34 m^2 area). Solar radiation data was obtained from the National Renewable Energy Lab (NREL) database, where solar radiation in this instance is defined as the solar power per unit area (m^2) observed on the earths surface from electromagnetic radiation from the sun. The quantity of solar radiation is inversely proportional to the distance from the sun squared (Iqbal, 2012). Wind velocity and surface temperature data was obtained from the NASA Surface meteorology and Solar Energy database; the databases are linked to the HOMER tool (HOMER Energy, 2016). The solar radiance, clearness index, surface temperature and wind velocity used in the modeling of the system are shown in Appendix C. The clearness index is automatically determined in HOMER by dividing the total global solar radiance by the extraterrestrial solar radiance giving a value that indicates the amount of solar irradiance penetrating the atmosphere (HOMER Energy, 2016). Sensitivity analysis was performed to determine the effect of diesel price, inflation rate, project lifespan and battery lifespan on the capital cost and the cost of energy; results are shown in Appendix C. The schematic of the systems simulation is shown in Fig. 4.3.

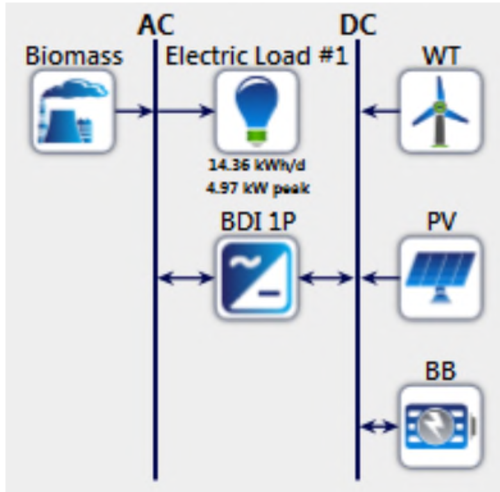


Figure 4.3. Schematic representation of the simulated system (HOMER Energy, 2016)

Fig. 4.3 is showing all the technology implemented in the Skye-Lab; for the other simulations some technology was removed from the schematic shown. The Eco-Lab didn't have the biomass system shown and the Grid-Lab only contained the battery bank (BB) and the inverter (BDI 1P) from the schematic; there was also a grid-supply (not shown) that catered for the load shown. The equations used in the HOMER for each of the power production technologies is shown below. The power output of the PV panel system is calculated with the Equation [4.3.] (Lambert *et al.*, 2006).

$$P_{PV} = f_{PV} Y_{PV} \frac{I_T}{I_S} \qquad \textbf{[4.3]}$$

In the equation P_{PV} is the total power output in kW; f_{PV} is the derating factor (kW); Y_{PV} is the rated capacity (kW); I_T is the solar radiation (kW/m^2) and I_S is the solar radiation standard of 1 kW/m^2.

The cost of energy of the generator is calculated with Equation [4.4.] (Lambert *et al.*, 2006)

$$c_{gen,fixed} = c_{om,gen} + \frac{c_{rep,gen}}{R_{gen}} + F_0 Y_{gen} c_{fuel,eff} \qquad \textbf{[4.4]}$$

$C_{om,gen}$ is the operation and maintenance (O&M) cost; $C_{rep,gen}$ is the replacement cost (USD), R_{gen} is the generator lifetime in hours, Y_{gen} is the capacity of the generator in kW and $C_{fuel,eff}$ is the price of fuel per Litre. The marginal energy cost ($C_{gen,mar}$) is calculated with Equation [4.5.], where F_1 is fuel consumed per hour per kilowatthour.

$$c_{gen,mar} = F_1 c_{fuel,eff} \qquad \textbf{[4.5]}$$

4.2.2. LOAD PROFILE FOR COMPARITIVE PURPOSES

The load profile (Fig. 4.4.) was predicted based on the power usage demands of the laboratory equipment and reverse osmosis system shown in Appendix A.7. To compare the power production of the renewable energy laboratories and the cost of energy all three laboratories were modeled with the load profile shown in Fig. 4.4.

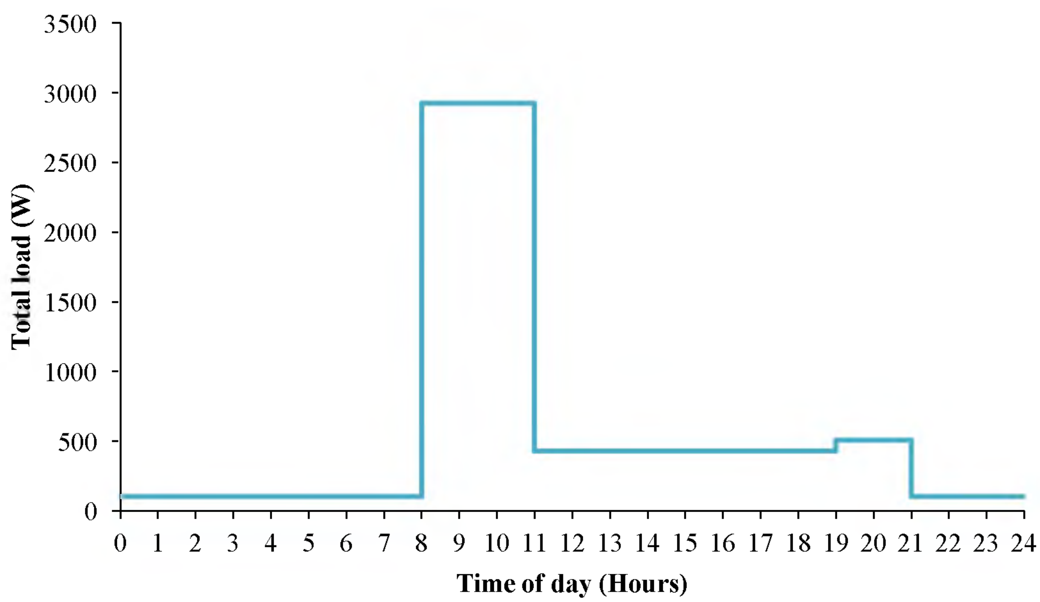


Figure 4.4. Simulated load profile for one 24-hour day

The operational schedule used to calculate the load profile is shown in Appendix A.7.

4.2.3. LOAD PROFILE FOR EACH LABORATORY

The load profile used to model the full techno-economic cost of each of the laboratories is shown in Fig. 4.5.

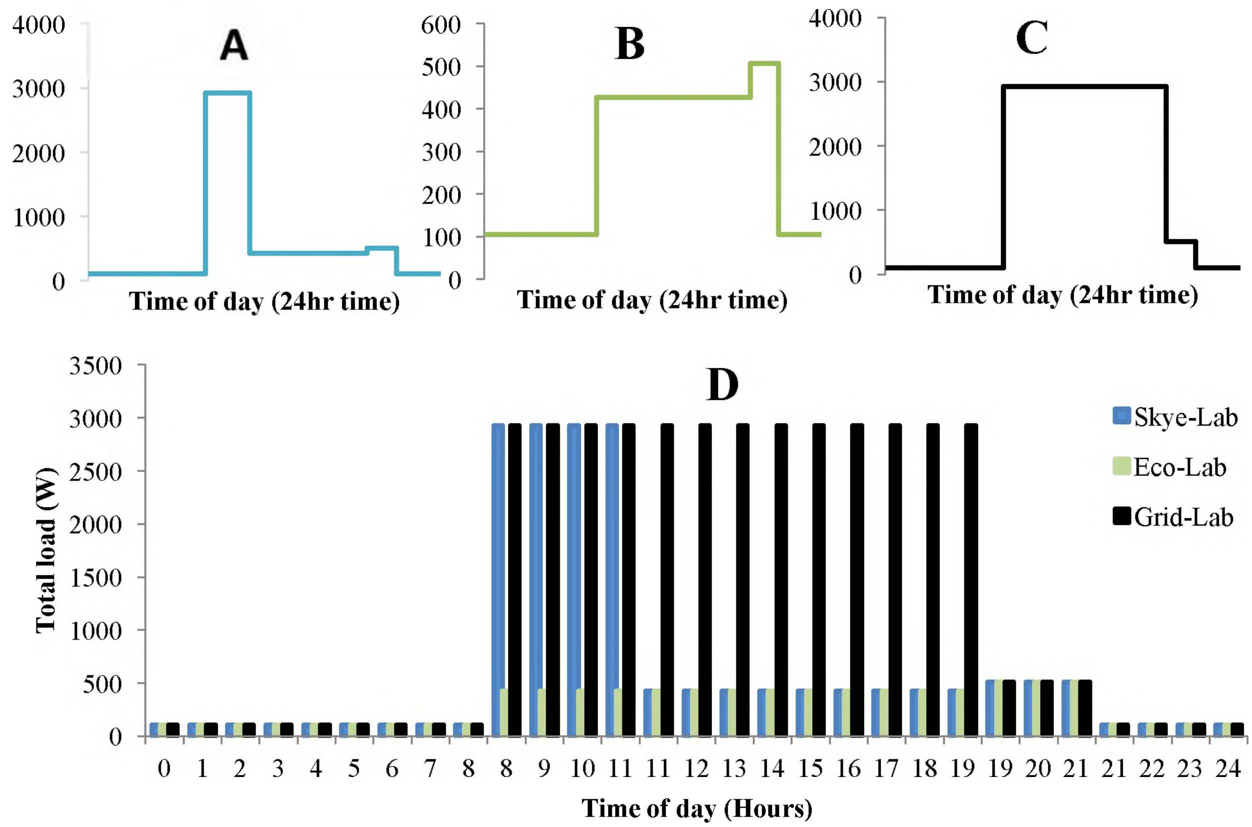


Figure 4.5. Load profile of different laboratory set-ups throughout a 24-hour day.

The load for the Skye-Lab shown in ***A*** was used for systems simulation and comparison as described in the results; the 3-hour peak shown is the operation of the RO system. For comparing the three different laboratories, different loads where modeled. The Load of the Eco-Lab is shown in ***B*** where the maximum load was less than 500 W and there was no load-intensive RO system. The Grid-Lab, shown in C, showed the load of the operation of the RO system for 12 hours. A comparison of the load profile of each laboratory is for a 24-hour time period is shown in ***D.***

4.2.3. COST BENEFIT AND SROI ANALYSIS

The primary stakeholders were identified as the rural population and the 'Government'. Their inputs were identified as time for the rural population and capital for the Government departments. The intended changes and the financial proxies used to quantify them for the each stakeholder are shown in Table 4.1.

Table 4.1. The financial proxies used to quantify the intended change for each stakeholder.

<table>
<tr><td rowspan="2">Intended change</td><td colspan="2">Financial proxies of each stakeholder</td></tr>
<tr><td>Rural population</td><td>Government</td></tr>
<tr><td>Decrease travel cost</td><td>Cost of travel- R 20 pp/trip (Molelekwa, 2016)</td><td>-</td></tr>
<tr><td>Decreased school truancy</td><td>-</td><td>Cost of truancy- R 23 857 pp/yr (Heady et al., 2007)</td></tr>
<tr><td>Decreased work absenteeism</td><td>-</td><td>Cost of labour force absenteeism- R 385 pp/day (See rationale below)</td></tr>
<tr><td>Increase disease diagnosis</td><td rowspan="3">The financial value of having improved sanitation- R 2802 pp (Kobel and Del Mistro, 2015)</td><td rowspan="3">Cost of improving sanitation – R 529 pp (Kobel and Del Mistro, 2015)</td></tr>
<tr><td>Increased water compliance monitoring</td></tr>
<tr><td>Decreased fatalities</td></tr>
<tr><td>Electricity supply</td><td>-</td><td>Cost of grid extension- R 1 494 425 per extension >5km (Deichmann et al., 2011)</td></tr>
<tr><td>Potable water supply</td><td>-</td><td>Cost of water supply extension- R 98 pp/yr (Kobel and Del Mistro, 2015)</td></tr>
</table>

4.2.3.1. COST SELECTION RATIONALE

4.2.3.1.1. COST OF TRAVEL

According to the spokesperson of the South African National Taxi Council (SANTACO) the price of a taxi in rural areas is approximately 10 ZAR per person per 5 to 10 km. It is difficult to get an accurate estimate because the taxis are not metered and the price varies depending on the routes taken (Molelekwa, 2016). For the travel cost calculation it will be assumed that individuals would be within 5 to 10 km from clinics prior to laboratory placement and the price of a taxi is 10 ZAR. Considering each of the 212 patients would have attended the clinic for diarrheal illness at least 1 day per annum (based on incidence) (NICD, 2015), the total value of not using transport is 20 ZAR per person per year.

4.2.3.1.2. COST OF LABOUR FORCE ABSENTEEISM

The maximum loss revenue for the 'government' stakeholder group was calculated with the number of days paid sick leave that each employee is required to receive. In South Africa, an employee (working 5 days a week) is required to receive 30 days paid sick leave per every 3 years; 10 days annually (My Wage, 2016). Of the national average annual paid sick leave taken, 7.93 % is attributed to gastro-intestinal illness (Occupational Care South Africa, 2016), equating to roughly 1 day per person per year of paid sick leave taken for diarrheal symptoms. Using this value and taking into consideration the average travel time of 73.6 minutes; which excludes the time at the clinic (Tanser *et al.*, 2006), a conservative estimate of 2 days paid leave is taken annually per person because of intestinal illness. With the mobile laboratories operating 6 days a week and until 7pm each day, the intended change is to eliminate the paid leave taken for intestinal-related diseases. Using the estimate of diagnosing 212 patients per year of which 139 will be of working age (Statistics South Africa, 2015b), and considering each of these patients would have otherwise taken 2 days sick leave, the total cost was calculated as 385 ZAR using the average rural income of 3852 ZAR per person per month working 20 days (Daniels *et al.*, 2013). This value does not take into account loss of productivity, which will influence the cost substantially.

4.2.3.1.3. COST OF POOR SANITATION AND WATER SUPPLY

According to Kobel and Del Mistro (2015), the value of one unit reduction in diarrheal incidences amongst 1000 people is 174.12 ZAR per year; this value takes into account the number of diarrheal infections per month, the number of school days lost due to diarrhoea per month, the number of water sources that do not comply with drinking water quality standards and the average amount of tax money spent by the government on medical care for diarrhoea. Considering the functions of laboratory serve to increase sanitation and diarrheal diagnosis there is an estimated reduction of 6.7 % diarrhoeal incidences per month based on the equivilent municipal intervention (Kobel and Del Mistro, 2015). Kobel and Del Mistro estimated the municipal investment cost to meet the sanitation needs of 266 883 households with shared facilities to be 7 840 901 ZAR per month; from a sample group surveys of 'willingness to pay' it was estimated that the benefit to the user was 41 550 725 ZAR per month. Considering the laboratory is estimated to provide adequate sanitation to benefit 212 citizens, the equivelent municipal cost 112 116.51 ZAR per annum and the estimated user benefit is 594 131.02 ZAR per annum.

4.2.3.1.4. COST OF POTABLE WATER SUPPLY

According to the Water Research Comminsion, providing potable water to a decentralized area costs an average of 1 400 ZAR per capita for the initial infrasturcture and then a further 280 ZAR per capita per decade for maintenance (Thompson *et al.*, 2009). This equates to 98 ZAR per person per year for the project period of 20 years that the government would have to spend to provide potable water. This value will be used to quantify the benefit of the Skye and Eco-Lab providing potable water to residents.

4.2.3.1.5. COST OF ELECTRICITY SUPPLY

Deichmann *et al.* (2011) states the cost of extending a municipal supply grid (11kV line) in sub-Saharan Africa to be 298 885.00 ZAR per Kilometer (Deichmann *et al.*, 2011). Using this estimate and the placement of the laboratory being a >5km from the closest substation, the total cost of extension can be calculated as 1 494 425 ZAR. This cost is not calculated per person as this is standard for the extension of the grid and it is irrespective of quantity of people provide for.

4.3. RESULTS AND DISCUSSION

For the purpose of systems comparison, three different laboratory set-ups were modeled. The detailed description of the three laboratories is provided in Chapter 2. As previously described the energy system for each laboratory was simulated in HOMER Pro and the operational and economic value was modeled. All costs and technical specifications used in the modeling are provided in Appendix A. Using HOMER results the forecasted electricity and water production of two of the laboratory systems was compared to the Grid-Laboratory. The TEA was performed according to the methods described, the quantifiable costs and benefits were isolated from the HOMER results and used in a Net Present Value (NPV) cost-benefit analysis. The social benefits were quantified in monetary terms with the SROI methodology. The overall benefit of the project was represented as the SROI ratio, calculated as NPV of Cost over NPV of Benefit.

4.3.1. SYSTEMS SIMULATION AND COMPARISON

The simulation served to gauge the parameters related to the operation of each laboratory namely; the annual electricity production, annual load profile, excess electricity produced along with the shortage, the renewable energy fraction and load that wasn't met (if any). The environmental impact of the system was assessed according to carbon, particulate matter, Sulphur dioxide and Nitrogen oxide emissions. The load was determined from the equipment chosen in Chapter 2 and for comparative purposes it was assumed that both the Eco- and Skye-Lab had identical loads (shown in the methodology). The simulation was performed with a load following control algorithm, with only enough electricity production to meet the needs of the load. Load following control systems have proved optimum in renewable energy power supply systems where the production far outweighs the predicted load (Zoulias and Lymberopoulos, 2007). The limitations set were as follows: the operation of more than one generator and was not allowed; the operation of the generator at less than peak load was prohibited; the orientation of the batteries in the battery bank was not specified-allowing for optimization. The cost-analysis of the energy system included a sensitivity analysis on the price of diesel and the availability of wood chips (for the biomass system). Due to the fluctuation in Diesel price throughout 2015 in South Africa (the simulation year) and the difference in price between inland and coastal regions (Engen, 2016), three values for Diesel were used for the sensitivity analysis, namely; 9, 10 and 11 ZAR per Litre. For the purpose of the emissions calculations Diesel (0.005 % Sulphur) was used because of the lower emissions to other alternatives. A 6, 7 and 8 % interest rate (per annum) and a 7 % discounted rate was used after consulting rates over the previous 10 years and the forecasts (Trading Economics, 2016). The price of "rural' electrification with the municipal supply was considered to be R2.86/kWh however, in addition the sensitivity analysis was performed with R0.93/kWh as the lowest cost (Eskom, 2016). Alternative durations of the project were modeled as 20, 25 and 30 years to determine the operations costs of extending the project lifespan.

4.3.1.1. RENEWABLE ELECTRICITY PRODUCTION

The Skye-Lab and Eco-Lab were optimized with the same load profile (the RO system along with all other lab equipment) as shown in methodology. The Skye-Lab system displayed 11 539 kWh cumulative annual electricity production, with a renewable energy fraction of 62 % (7154 kWh). With the remainder of power produced by the biomass generator, which used wood shavings to minimize Diesel consumption, indicating that the renewable energy fraction would have been higher if this variable was taken into consideration. The Eco-Lab produced a cumulative annual production of 9408 kWh with 100 % renewable energy fraction. The Skye-Lab was able to cope with the load of the simulated system generating 6036 kWh excess electricity whilst the Eco-Lab had an unmet load of 286 kWh with the current simulation. The cumulative annual load that the Eco-Lab is able to provide for is 4955 kWh; modifications in the operational schedule of the RO system will sort to meet the Eco-Lab system capabilities. Table 4.2. demonstrates the electricity production and demand for the laboratories' simulated energy system.

Table 4.2. Electricity production and demand for the simulated systems

Cumulative annual electricity production		
	Skye-Lab	Eco-Lab
PV panels	7751 kWh/yr	7751 kWh/yr
Wind System	1657 kWh/yr	1657 kWh/yr
Biomass	2331 kWh/yr	-
Total	11539 kWh/yr	9408 kWh/yr
Renewable energy fraction	62 %	100 %
Cumulative annual load served		
AC primary load	5241 kWh/yr	4955 kWh/yr
Other		
Excess electricity	6036 kWh/yr	4001 kWh/yr
Capacity Shortage	0 kWh/hr	519 kWh/yr
CO_2 emissions	2603 kg/yr	0 kg/yr

According to Table 4.2. 6036 and 4955 kWh/yr excess electricity was generated by the Skye and Eco-Lab respectively; this is partly due to optimum number of batteries being modeled to ensure the overnight load was catered for. The optimum number of batteries in the battery bank was modeled as 8 connected as 2 strings of 4 in parallel for the Skye-Lab and 16 connected in 4 strings of 4 in parallel for the Eco-Lab. The Eco-Lab required a larger battery bank to ensure the throughput was enough to cater for the load required. The Skye-Lab BB had an annual throughput of 798.77 kWh with 126.98 kWh/yr losses whilst the more utilized Eco-Lab BB had an annual throughput of 1527.20 kWh with 243.01 kWh annual losses. The expected life of both BB operating at this capacity was 3 to 4 years. The excess electricity generated could serve the community if the BB of either laboratory were to increase in size or the excess electricity could be fed straight into a temporary local grid (Pegels, 2010). Another reason for the excess electricity generation is that the load is standard on a daily schedule, however seasonal differences affect the energy producing systems. The biomass system was simulated to schedule based on the intensity of the load; which means the power produced is the same throughout the year. During the summer months, the PV system produces more electricity and therefore the biomass system creates an overall excess. The monthly average of electricity production by each system is shown in Fig. 4.6. and Fig. 4.7.

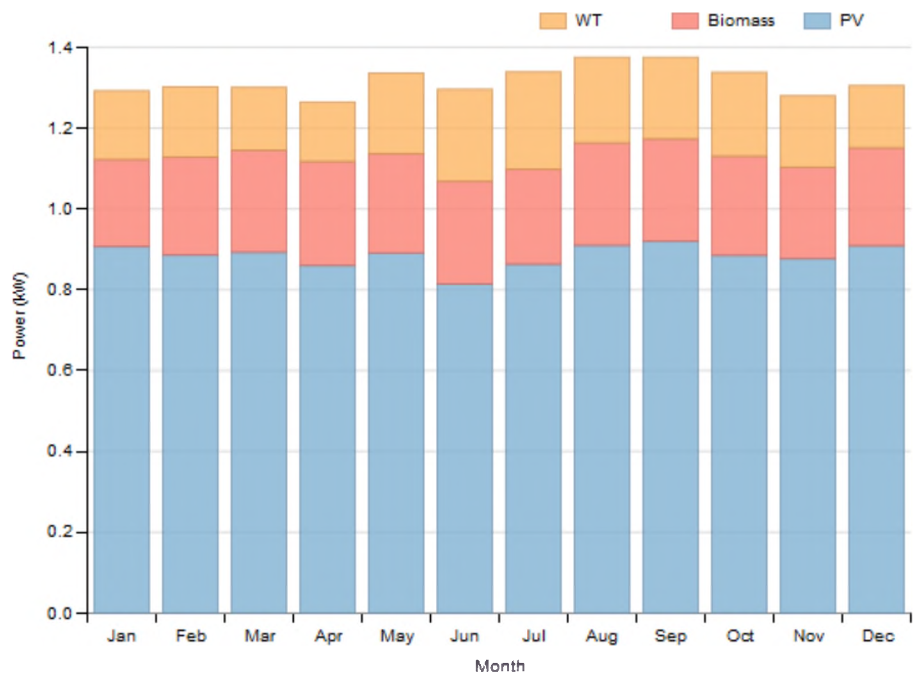


Figure 4.6. Simulated power output for the Skye-Lab

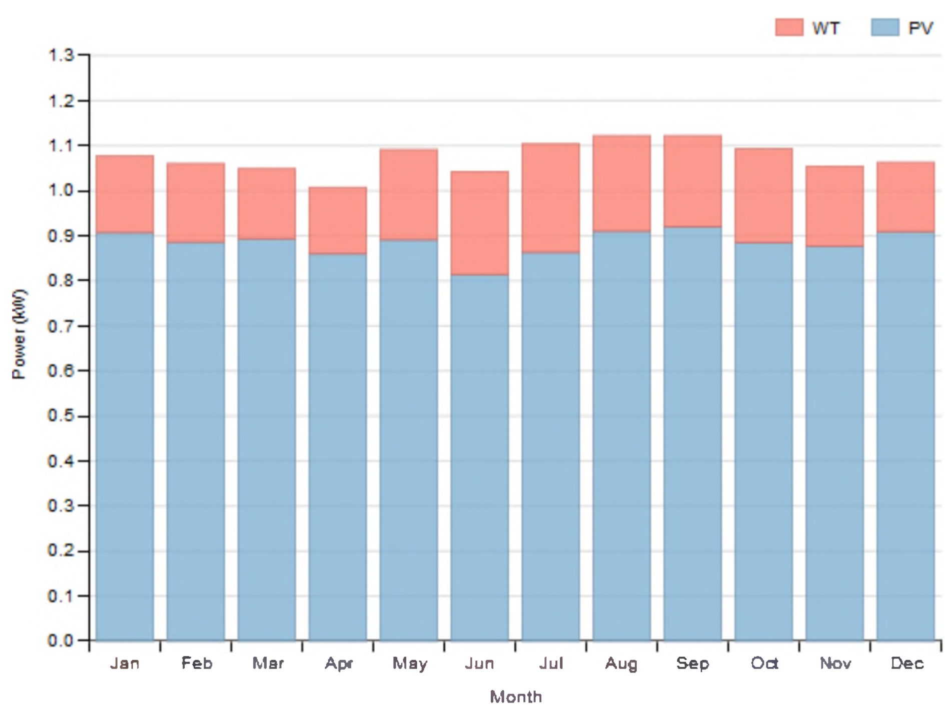


Figure 4.7. Simulated power output for the Eco-Lab

The total energy output simulated with HOMER Pro for both systems in the year 2015 is shown in Fig. 4.6. and 4.7. Biomass represents the power produced from the biomass system, WT represents the power-produced form the Wind turbine and PV represents the power output from the photovoltaic system. The variation in power output is due to the average temperature, wind speed and solar radiation cause by seasonal variation in the chosen location in Grahamstown, South Africa. In the Southern hemisphere winter occurs from the beginning of June to the end of August; during which there is a decreased temperature and solar radiance due to the change in the earths rotational axis and there the decreased incident angle of the sun and increased distance between the earth and the sun (Khavrus and Shelevytsky, 2012). Conversely, wind velocity increases in winter due to the lower atmospheric pressure over the poles (Smith *et al.*, 2005). The peak month for power production was August, this is because of higher wind speeds and solar radiation experienced in that month. The solar, wind and surface temperature data will invariably differ in different locations. It is therefore important to consider the data available in the specific location to gauge the size of the power systems needed.

4.3.1.2. COST COMPARISON OF ENERGY SYSTEMS

The HOMER simulation took place with the most recent costing data available for all the equipment necessary (Appendix A). For the comparative purposes the load following algorithm was used for all three laboratories with the same load. The following table represents the annualized cost of the laboratories over their lifespan. For the simulation all the sensitivity parameters modeled were assumed to be similar to present values in South Africa for the years 2015/16. The interest rate was 7 % (Trading Economics, 2016); Diesel was 10 ZAR/L (Engen, 2016); the project lifespan was considered to be 20 years; the lifetime of the batteries 5 years (Sustainable Inc., 2016) and the price of electricity 2.86 ZAR/kWh (Eskom, 2016). The high price of electricity is because the tariff was chosen for decentralized electrification; this is because it allows for the comparison of far-reaching municipal supply to off-the-grid systems.

Table 4.3. Distribution of total annualized costs for the equipment incorporated into the laboratories

	Skye-Lab	Eco-Lab	Grid-Lab
Biomass	R 41929	-	-
PV panels	R 4220	R 4220	-
Wind System	R 3082	R 3082	-
Inverter	R 3737	R 3737	R 3737
Battery Bank	R 905	R 1810	R 113
Grid Supply	-	-	R 14983
System total	R 39248	R 12850	R 18833
Levelized cost of energy	10,28 R/kWh	2,59 R/kWh	3,59 R/kWh

The initial cost of the biomass system increased the annualized cost of the Skye-Lab substantially when compared to the Eco-Lab; the total annualized cost of the system related to a levelized cost of energy of 10.28 ZAR/kWh compared to the Eco-Labs' 2.59 ZAR/kWh. Considering the relatively small difference in annual electricity production an increase of approximately 8 ZAR per kWh is not economically viable. In the design criterion, the Grid-Lab required a back-up power storage to ensure operations weren't interrupted; a smaller 1 kWh inverter was optimized as well as a smaller BB consisting of 1 string of 4 batteries. The cost of the back-up power system added to the total annualized cost of the system. The cost of energy for the Grid-Lab was therefore R 1 higher per kWh produced; nevertheless the price of electricity used (2.86 ZAR/kWh) was higher than the cost of energy provided by the Eco-Lab, suggesting that the Eco-Lab is a feasible option for power production at the load simulated and in a rural setting.

The sensitivity analysis showed a substantial increase in the operations and management cost of the Grid-Lab with the increase in power price. This is shown in Fig. 4.8.

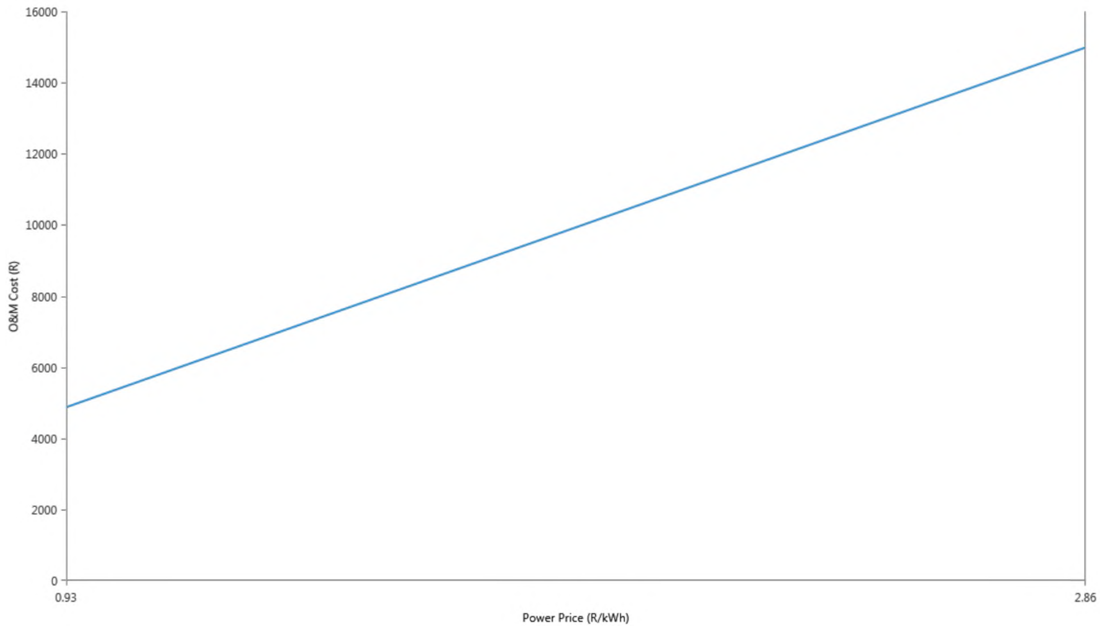


Figure 4.8. The effect of the increase in electricity rates on the operation and management cost of the Grid-Lab

Comparatively the operating cost of the Eco-Lab was shown to decrease with the increase in battery life (shown in Fig. 4.9.); however even with the battery life of 3 years the annualized total operating cost of 3000 ZAR was less than the 5000 ZAR of the Grid-Lab with the lowest power price used.

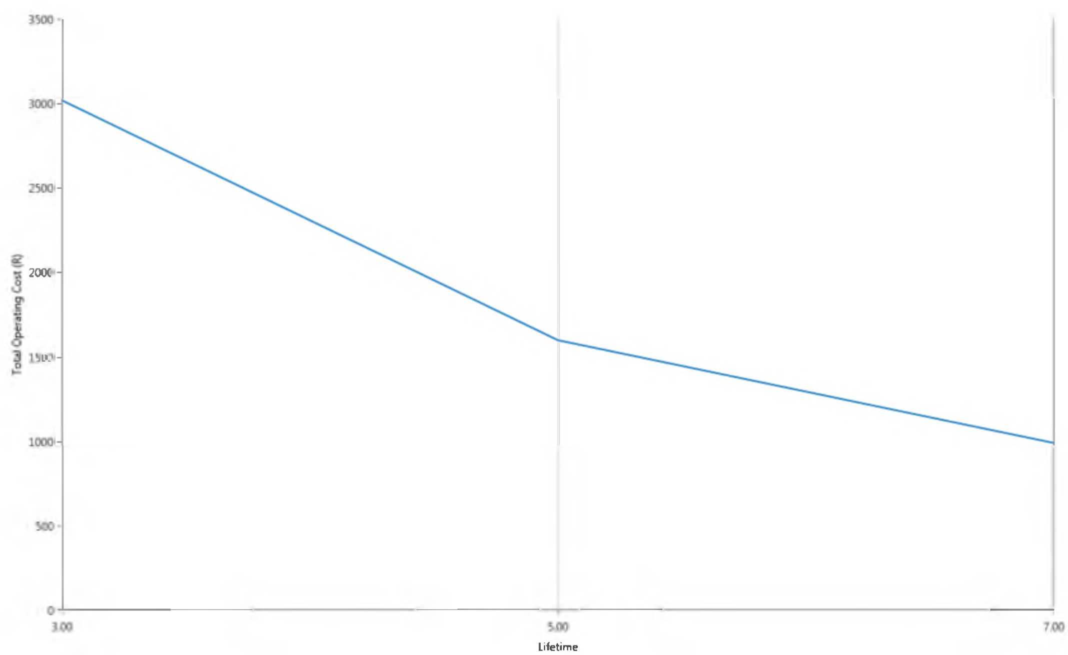


Figure 4.9. The effect of battery life on the total operating cost of the Eco-Lab

The annualized total operating cost for the Skye-Lab was directly correlated with the increase in Diesel price as shown in Fig. 4.10. The annual cost at the current rate diesel price (10.52 R/L) is approximately 15 400 ZAR; this could increase to 16 000 ZAR in the next year with the rise of diesel price to 11 R/L.

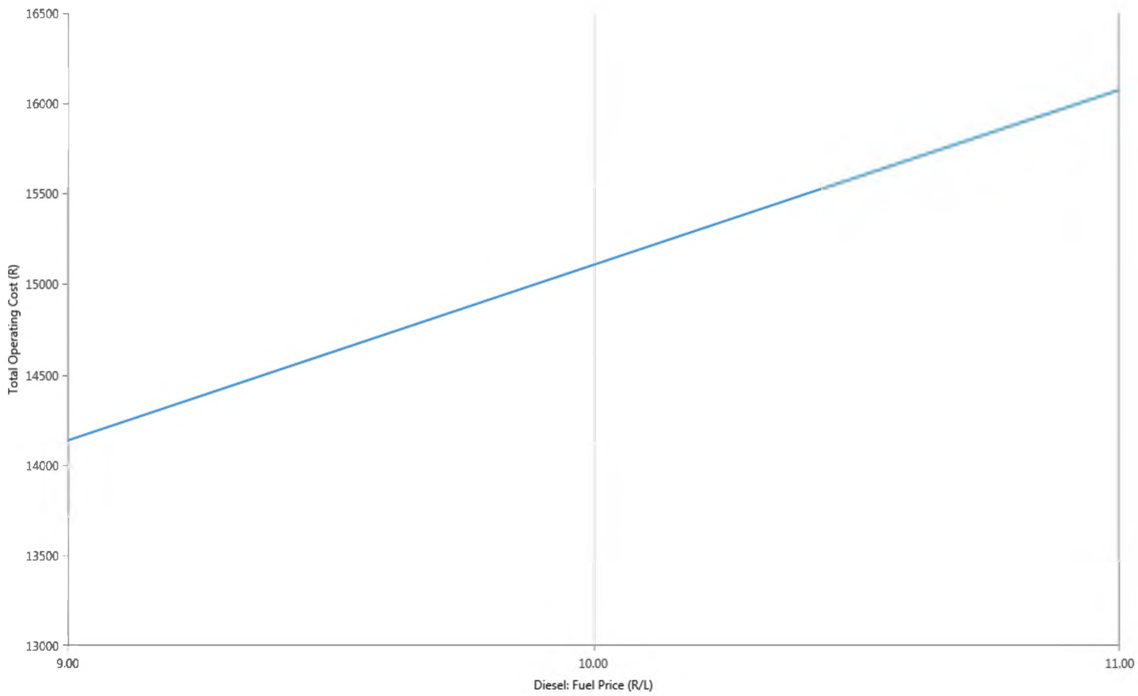


Figure 4.10. The effect of diesel price on operating costs of the Skye-Lab

4.3.2. OVERALL COST ANALYSIS

4.3.2.1. INDIVIDUAL LABORATORY MODELING

For comparative purposes of the electricity production and its cost the laboratories were modeled with the same load profile; however, for placement each laboratory will serve for different needs (as described in Chapter 2) and will therefore have different load profiles. The load profile for each laboratory is shown in the methodology. The production of electricity and water from the three laboratories was simulated with energy output of the equipment selected and the load of the laboratory equipment using the load following algorithm in the HOMER tool. Fig. 4.11. shows the cumulative electricity output by the power producing equipment for the three laboratories over the year 2015.

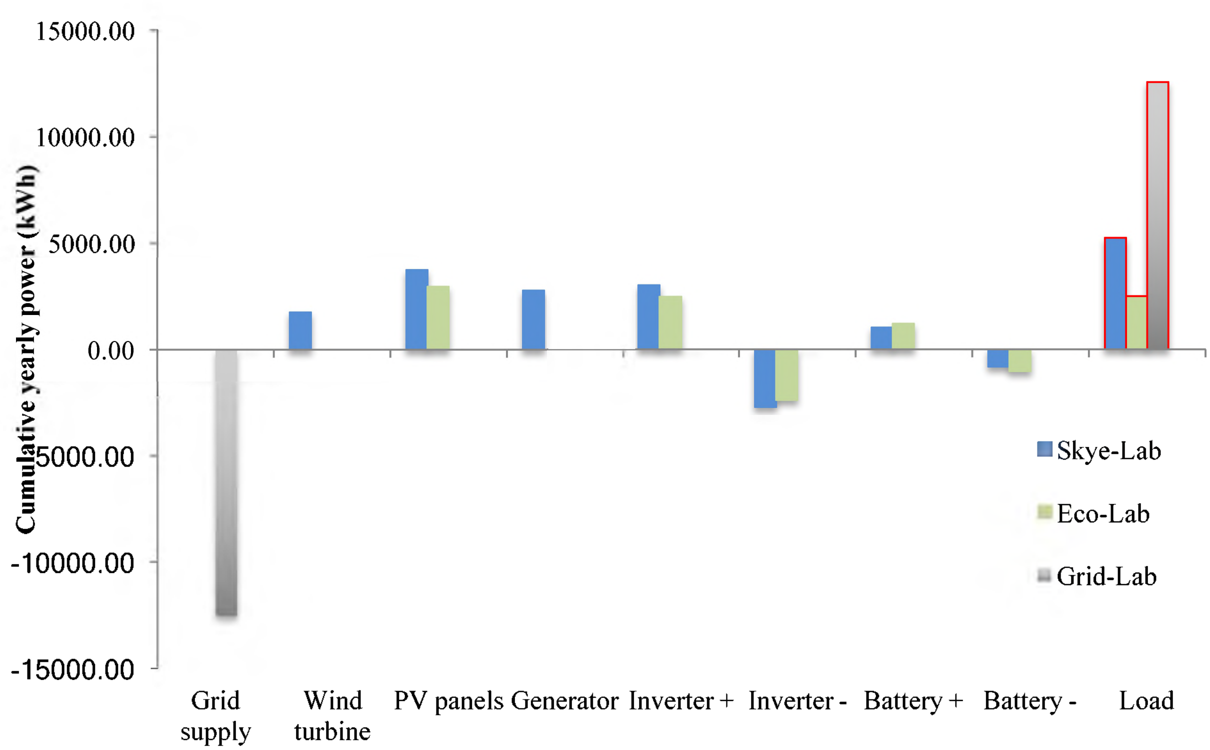


Figure 4.11. The total yearly electricity production and load for the simulated systems in Grahamstown, South Africa

The Eco-Lab was designed primarily to provide disease diagnosis and water compliance monitoring off-the-grid. The optimized system excluded the use of the wind system due to economic considerations; seven 250 W solar panels with an annual cumulative production of 2953 kWh and 3 strings of 4 batteries in parallel was sufficient to provide for the necessary load profile of 2471 kWh/yr with an excess production of 311 kWh/yr. The optimal system control strategy was 'cycle-charging' as all the power produced by the PV system was used to charge the batteries and the laboratory equipment ran solely of the batteries. Although a continuous power supply is always available with this dispatch strategy, it can lead to battery erosion and more electrical losses during conversion which translates into shorter battery lifetime and less energy efficiency (Barley *et al.*, 1995). The cost of energy (COE) was calculated to be 4.51 ZAR/kWh which is similar to the 3.73 – 4.47 ZAR/kWh found by Rehman *et al.* (2007) with a similar PV system. This is 30 % higher than the grid supply which is relatively low; Beccali *et al*. (2008) showed a 70 % increase in COE compared to grid supply.

The Skye-Lab was designed to provide electricity and water as well as water compliance monitoring and disease diagnosis in an off-the-grid situation. The system was optimized to produce excess electricity and it was optimized with the use of 21 250 W PV panels producing a total of 7751 kWh/yr with a penetration of 147.88 %; the Biomass generator simulated produced 2131 kWh/yr for 852 hours of operation consuming 961 L of diesel; the wind system produced 1657 kWh/yr with a penetration of 31.61 %. The renewable energy penetration in this case was calculated as the maximum kWh output divided by the load kWh. The PV penetration of 147.88 % therefore means that the PV system produced enough power to cater for the load and 47.88 % more; similar penetration was shown by Hoke *et al*. (2012) with the same dispatch strategy indicating that PV systems are imperative for off-grid power generation (Hoke *et al*., 2012). Conversely the wind penetration of 31.61 % is lower than 50 % simulated by Jiang *et al*. (2012); the low penetration is partly due to the undersized 1 kW wind turbine used and due to the low wind resource available in the chosen location (Jiang *et al*., 2012). The optimized battery bank consisted of 2 strings of 4 batteries in parallel and had an annual throughput of 799 kWh/yr. The dispatch strategy was load following, which meant that the batteries were charged with the renewable system only and the generator was used for to provide the load required for the RO system. Load following dispatch was favoured because of the high renewable energy penetration (specifically the PV penetration) (Barley *et al*., 1995). The AC primary load of 5241 kWh for the year was met providing 6036 kWh/yr excess electricity at 10.28 ZAR/kWh with 2602 kg/yr carbon dioxide emissions. Based on the World Bank statistics mean electricity per person in 2013 of 3 104 kWh the excess electricity produced can be used for 2 individuals (OECD and IEA, 2014). In a similar off-the-grid situation providing for a load of 11 534 kWh/yr, Al-Karaghouli and Kazmerski (2010) found a COE for the solar-alone system to be 3.41 ZAR/kWh and 19.10 ZAR/kWh for a combined solar-diesel hybrid system. The COE of the optimized Skye-Lab system is therefore lower than the solar-diesel system, this together with the adaptability of the multiple-source power generation make it an attractive choice for providing a greater off-the-grid load. With the current placement and the low wind energy penetration, the cost of energy could be lowered to 9.80 ZAR/L with the exclusion of the wind system; however, for the cost considerations it will be included to provide the upper limit of the price range and because it may be useful in situational placements where solar resources are low and wind is in abundance. Based on the schedule of operation of the RO system in the Skye-Lab it can provide 213 people with 3.7 L of drinking water per day (see Chapter 2 for reasoning) at the levelized cost of 11.37 ZAR/L. The cost of municipal piped water supply in South Africa ranges from 1 to 4 ZAR per 1000 L (Eberhard, 2015); more appropriately Lienhard *et al*. (2012) found the cost of water in an off-the-grid situation to be between 42.94 and 186.06 ZAR/1000 L using a PV powered reverse osmosis system and between 83.01 and 229.00 ZAR/1000 L using electrodialysis. Although the cost of water is substantially higher with the Skye-Lab, the sole purpose of the Lab is not providing water and the other benefits need to be taken into consideration.

The Grid-Lab had the primary purpose of providing large quantities of water with the standard water compliance monitoring and disease diagnosis functions. The system was optimized with a battery bank consisting of 1 string of 4 batteries and an inverter to charge them from the grid supply. The dispatch strategy was load following for the operation of the RO system and the batteries provided the power for all other laboratory equipment. Based on the cost of electricity of 3.16 R/kWh and the operational schedule of the RO system the Grid laboratory can produce 3157 L; providing 854 persons with their required potable water per day at 30 ZAR/kL which is lower than the lowest cost of water found by Lienhard *et al*. (2012) of 42.94 ZAR/kL using a reverse osmosis system. The carbon dioxide emissions of the grid supply was substantially higher than the Skye-Lab with 7922 compared to 2602 kg per year, indicating that the environmental cost of the Grid-Lab is not preferable especially in situations where water is not a priority.

4.3.2.2. TOTAL NET PRESENT COST

The total net present cost shows the total capital required for the project duration of 20 years. It is important to include the entire cost of the project duration in the cost-benefit analysis performed in this Chapter because the benefits of the laboratory placement are long term; the benefits of such a project are multifaceted and can only be fully evaluated over a period of 20 years. A summary of the net present cost for the implementation and function of each laboratory as individually modeled for the project lifetime (20 years) is shown in Table 4.4. Previously mentioned inflation rates, diesel prices and salary increases were taking into consideration when calculating the net present cost of each of the laboratories.

Table 4.4. Total net present cost in ZAR for each laboratory over the 20 year project period.

	Skye-Lab	Eco-Lab	Grid-Lab
Energy systems total	R 977 724	R 121 645	R 719 697
Lab equipment total	R 1 102 415	R 931 046	R 1 102 415
Container, modifications and other equipment	R 93 513	R 93 513	R 93 513
Payment for operator	R 2 459 728	R 2 459 728	R 2 459 728
Net present cost	R 4 633 380	R 3 605 932	R 4 375 353

The energy systems cost for the Eco-lab was substantially lower than the other two laboratories; this is because the Eco-Lab did not have the biomass generator or the wind turbine like Skye-Lab, and was not reliant on the municipal supply like the Grid-Lab. The operating costs were therefore kept to a minimum because the fuel for the biomass system and the cost of municipal power supply was not included. The only operating cost that pertaining to the Eco-Lab was the replacement of batteries, which due to the cycle-charging dispatch strategy had a shorter life-span than the other two laboratories. The laboratory equipment cost for each lab for the most part standard, except with the exclusion of the RO system and membrane replacement cost in the Eco-Lab as water treatment wasn't considered. The water tank and pump was still included in the calculation as rain-water harvesting and a closed cycle filtration set-up will be used to provide water for the laboratory operator. The other laboratory equipment costs were included as described in the introduction. The cost of disease diagnosis and water compliance monitoring kits was calculated as described; the cost of inflation for these was not considered the cost is expected to decrease as the technology becomes more readily available, although an overall contingency factor of 1.07 was applied for unexpected advances in technology or changes in legislation. The container, modification and other lab equipment was standard for all three laboratories; the other equipment included items such as a transceiver, laptop, ventilation fans, lighting and furnishing. No inflation rate or contingency factor was considered because these costs were considered once-off, tenable at the project inception. The payment for the laboratory operator was considered standard for all three laboratories despites slight differences in duties. The salary was considered according to the expected skill level, the laboratory placement and the operations schedule according to the Basic Conditions for Employment Act (Department of Labour, 2016). A salary increase of 7 % per annum was considered according to the current nominal interest rate (Trading Economics, 2016). The total net present cost of Skye-, Eco- and Grid-Lab was calculated to be 4.6, 3.6, and 4.3 million ZAR for the 20-year duration of the project.

In 2015, the NHLS total expenditure for surveillance of communicable diseases was 167 million and on laboratory tests 4.9 billion for the 62.5 million laboratory tests performed crudely calculated as equating to 78.4 ZAR per test.

4.3.2.3. TOTAL NET PRESENT BENEFIT

The total net benefit in monetary terms was calculated over the 20-year project period using the rationale detailed in the methodology. The nominal annual inflation rate of 7 % was used in the calculations. The total value of the placement of the laboratory for each citizen was calculated to be 598 370 ZAR; taking into account the intrinsic value of sanitation to the individual and the travel costs saved. The total cost for the 'government' of not having the laboratory in place or alternatively providing equal services was calculated to be 1 644 478 ZAR. The value of water production by the Grid-Lab was calculated to be 83 692 ZAR and power and water production by the Skye-Lab 1 515 200 ZAR. The value of power production was very high because the cost of extending the municipal supply grid to the decentralized location (>5km) was used as a financial proxy.

4.3.2.4. COST BENEFIT RATIO

The value of the costs determined and optimized with HOMER Pro and the benefits quantified with the SROI methodology are shown in Table 4.5. The cost-benefit ratio (Eq. 4.1.) was calculated by dividing the total benefits by the cost of the intervention; the ratio represents the total ZAR return for every one ZAR capital investment. The cost benefit ratio is important to determine whether the specific intervention is economically viable and in fact worth implementing. It is also acts as means for comparison between different projects before implementation.

Table 4.5. The total value of costs and benefits as shown as a ratio (Eq. 4.1.)

	Skye-Lab	Eco-Lab	Grid-Lab
Net present benefit	R 14 542 464	R 8 679 115	R 9 002 976
Net present cost	R 4 633 380	R 3 605 932	R 4 375 353
Cost benefit ratio	1:3.13	1:2.41	1:2.06

As shown in Table 4.5. the Skye-Lab has the highest cost-benefit ratio, indicating that for every 1 ZAR invested there is a return of 3.13 ZAR. As previously mentioned the cost of extending the municipal grid was used as a financial proxy; this skewed the true benefit of the Skye-Lab as the minimum cost of extension is standard and can cater for up to 10 000 people, whereas the Skye Lab can only provide electricity to meet the daily needs of 10 citizens.
The cost of electricity per person per month couldn't be used as a financial proxy because in electrified rural areas residents benefit from 'free basic electricity' which is of no expense to them (Ruiters, 2009). For lack of a more appropriate financial proxy there is an observable inaccuracy with the cost-benefit ratio relating to the Skye-Lab, with the exclusion of the electricity production the Skye-Lab yield a 1.89 ZAR return for every 1 ZAR invested which is more realistic for its functions. The Grid-Lab provides potable water for substantially more people than the Sky-Lab and it has a relatively high return on investment of 2.06 ZAR per every 1 ZAR invested. It must be noted that the cost of water infrastructure was taken into consideration as the financial proxy to value water supply. There are major limitations with this proxy as the infrastructure put in place will provide on-tap supply to each residence, which could be valued higher than 'collectable' water from the laboratory by the

residents (Castro *et al.*, 2014). Additionally, the maintenance costs of the infrastructure may be less than the laboratory over a much longer term. The laboratory can provide potable water in far less time than the construction of infrastructure, which could take up to 3 years (Majuru *et al.*, 2012). The mobile laboratory is more apt to serve as a disaster management strategy. Mobile water treatment systems have shown promise in the management of disasters (Loo *et al.*, 2012). Considering the other functions of the laboratory it is a good rate of return for an emergency situation. The Eco-Lab has the lowest NPC and the highest rate of return; with every 1 ZAR invested relating to 2.41 ZAR return. This laboratory does not provide excess water or power and these financial proxies were therefore excluded from the benefit. The benefit was based solely on the laboratory placement and its disease diagnosis and water compliance monitoring function. The estimated travel costs were taken into account for rural population and overall increase in sanitation was predicted based on the location of the laboratory and its functions. The intrinsic value of this increase in sanitation to the citizens and the value to the 'government' was taken into consideration. A strong motivation was put forward by Hutton *et al.* (2007) for investment in improving water supply and sanitation; estimating a benefit of 5 ZAR for every 1 ZAR invested based on 'willingness to pay' survey responses.

Each of the laboratories have their unique combination of functions that suite displacement in a specific situation, therefore it is difficult to compare their cost-benefit ratios. With the recent emergence of this technique for SROI analysis, most of the databases are relatively new and don't include a large amount of values, some database are expensive to access but more importantly, there is no South African financial proxy database. A number of figures in the databases are based on the census and budget of the particular country in which the database is found, making it difficult to translate values to other countries. Although using these values is not ideal and may result in certain inaccuracies it is the best academically reviewed cost data available.

No valuations have previously been performed in South Africa or in fact any developing country. A detailed analysis performed by mixed methods is required to accurately determine a financial proxy and although the SROI methodology was stringently adhered to, for lack of better proxies and a multidisciplinary research group to calculate them there are inaccuracies present. This SROI analysis should therefore not be considered a 'gold standard' because it has only taken into account ***some*** of the benefits the designed laboratories could have on the selected stakeholders. It will also aid future research into identifying and quantifying financial proxies for a rural area in a developing country. For future research financial proxies should be determined by 'willingness to pay' surveys (HACT, 2016).

4.4. CONCLUSION

The comparison of the three laboratories with the same load profile indicated that for the renewable energy Skye and Eco-Lab the 1 kW wind turbine was not economically viable to meet the load in the given geographical location. The Eco-Lab had an unmet load of 287 kWh in meeting the load profile DD, WCM and RO equipment, this could be rectified by reducing the operating times of RO equipment. The cost of energy in the Eco-Lab with the standard load profile was the lowest with 2.59 ZAR/kWh, which is 39 % than the Grid-Lab for providing the same functions. The Skye-Lab produces an excess of 6036 kWh electricity although the 10.28 ZAR/kWh was substantially higher then the cost of energy of the other two laboratories. The biomass system increased the annualized cost of equipment 2 fold higher than the Grid-Lab. The Grid-Lab's annualized cost was 32 % higher than the Eco-Lab due to the increased operations and management cost caused by the price of Diesel.

A sensitivity analysis was performed on the effect of electricity rates, battery life and Diesel on the Grid-Lab, Eco-Lab and Skye-Lab respectively; the load profile for each was constant. The annualized operations and management cost of the Grid-Lab were shown to increase from 5000 ZAR to above 14 000 ZAR with the cost of electricity fluctuating from 0.93 to 2.86 ZAR per kWh. The annualized operating cost of the Eco-Lab was shown to decrease with the increase in battery life (shown in Fig. 4.9.); with a lifetime of 3 year resulting in the annualized O&M of 3000 ZAR and for 7 years, 1100 ZAR. Comparatively, even with the minimum battery lifespan the annualized operating cost is still approximately 40 % less than the minimum operating cost of the Grid-Lab. The annualized operating cost of the Skye-Lab was shown to increase with the increase in Diesel price with the current price (10.52 R/L) the annualized operating cost is approximately 15 400 ZAR. An increase of 0.50 ZAR/L in the Diesel price would result in an annualized operating cost in excess of 16 000 ZAR. With the incorporation of the biomass generator into the Skye-Lab there is an increased power producing capability. In a closed system, with the same load required for each laboratory the operating costs and the overall increase in cost of energy decreases the economic viability. To give a more accurate estimate of economic viability each of the laboratories were modeled and then optimized with load profiles specific to a particular function.

The optimized Eco-Lab system consisted of seven 250 W solar panels with an annual cumulative production of 2953 kWh and 3 strings of 4 batteries in parallel was sufficient to provide for the necessary load profile of 2471 kWh/yr with an excess production of 311 kWh/yr. The Wind turbine was not economically viable in the geographical location selected and was therefore excluded. The optimal system control strategy was ‘cycle-charging’. Although a continuous power supply is always available with this dispatch strategy it can lead to battery erosion and more electrical losses during conversion which translates into shorter battery lifetime and less energy efficiency (Barley *et al.*, 1995). The cost of energy was calculated to be 4.51 ZAR/kWh with 0 carbon dioxide emissions.

The optimized Skye-Lab consisted of 21x250 W PV panels producing a total of 7751 kWh/yr with a penetration of 147.88 %; the Biomass generator simulated produced 2131 kWh/yr for 852 hours of operation consuming 961 L of diesel; the wind system produced 1657 kWh/yr with a penetration of 31.61 %. Similar renewable energy penetration was shown by Hoke *et al.* (2012) with the same dispatch strategy indicating that PV systems are imperative for off-grid power generation (Hoke *et al.*, 2012). Conversely the wind penetration of 31.61 % is lower than 50 % simulated by Jiang *et al.* (2012); the low penetration is partly due to the undersized 1 kW wind turbine used and due to the low wind resource available in the chosen location (Jiang *et al.*, 2012). The optimized battery bank consisted of 2 strings of 4 batteries in parallel and had an annual throughput of 799 kWh/yr. The dispatch strategy was load following. The AC primary load of 5241 kWh for the year was met providing 6036 kWh/yr excess electricity at 10.28 R/kWh with 2602 kg/yr carbon dioxide emissions. Based on the schedule of operation of the RO system incorporated the Skye-Lab can provide 212 people with 3.7 L of water per day (see Chapter 2 for reasoning) at the cost of 11.37 R/L. The wind system should be scaled up to have a positive effect on the cost of energy; currently for the small-scale, in the location simulated, the conversion losses and the capital cost of the wind system outweigh its maximum kWh production. Although the wind turbine was included in the design of the

Skye-Lab to allow for hybrid source power generation as a proof of concept it was not economically viable.

The optimized Grid-Lab system consisted of a battery bank of 1 string of 4 batteries and an inverter to charge them from the grid supply. The dispatch strategy was load-following for the operation of the RO system and cycle charging for the batteries that provided power for all other laboratory equipment. Based on the current cost of electricity (3.16 ZAR/kWh) and the operational schedule of the RO system, the Grid-Lab can produce 3157 L; providing 854 persons with their required potable water per day at 0.03 ZAR/L. The carbon dioxide emissions were 7922 kg/yr.

The Net Present Cost of each of the laboratories for the 20-year project period was calculated; the NPC of the Eco-Lab was 18 % and 22 % less than the Grid-Lab and Skye-Lab respectively. The benefits of each of the laboratories on a rural population and the 'government' were quantified in monetary terms with the SROI methodology. The cost-benefit ratios were calculated for each laboratory and their associated benefits. The Eco-Lab had the best cost-benefit ratio with every 1 ZAR capital invested returning 2.41 ZAR in benefits. The limitations in the SROI methodology were identified as the lack of empirical financial proxies in South Africa and developing countries. Additionally, the methodology sorts to identify the beneficiaries to a given project but does not necessarily identify the possible financers; especially with the varied benefits of this project, no single government department, municipality, province, private entities of population are able to finance the whole cost of the project yet a large amount will receive benefit from it. In progressing with the prototype of one of the laboratories a coordinated financing model involving multiple stakeholders should be considered along with the specific demands of each of the stakeholders. In addition, concurrent interdisciplinary research with mixed methods is required to fully quantify the benefits for the stakeholders and possible future investors. Benefits such as the impact the mobile laboratory would have on sanitation and diarrheal awareness in the area of deployment should be evaluated in future research. The development of a social value database in South Africa is required especially with the increase in formal standards and performance measures in social enterprises (Millar and Hall, 2013).

In addition, it may have been beneficial to identify, from the community perspective, the value for the long-term impacts of the laboratory deployment that are not immediately apparent. The project was modelled within a conventional economic demand vs. supply economic model; during the SROI analysis the monetary benefit was quantified within the context of a 'perfect' competition and 'perfect' intelligence. However, the module was primarily designed for deployment in a disaster situation in which, the conventional market norms do not apply. Perfect information, whilst rarely prevalent in conventional markets, is significantly lacking in disaster situations (Van de Walle and Turoff 2008). Similarly, perfect competition is unlikely to occur due to the decreased number of suppliers and the resultant reduction in consumer choice. Furthermore, the individuals receiving humanitarian aid are not comparable to consumers due to their inability to make rational decisions based on the price and quality of a particular product (Mays *et al.*, 2012). Despite identifying these limitations to the SROI model used, there is a vital lack of understanding of the constraints and assumptions proposed by other non-conventional market models; and, when producing an economic model, complexity theorem states that more real-world assumption used the greater the accuracy of the model. Future research into the SROI methodology is required to develop separate humanitarian economic models that do not operate on the demand vs. supply assumptions and rather focus on quantifying the humanitarian need from a community perspective.

As a further recommendation for future research into the implementation of a prototype laboratory in a decentralized/disaster area, a laboratory producing power and water could be placed adjacent to a temporary/permanent school. The laboratory could address disease diagnosis as detailed throughout this paper except students in the form of portable batteries and refillable water tanks could take power and water home. The batteries and tanks would be refilled whilst at School each day. This could provide an incentive to increase School attendance and increase awareness about disease diagnosis simultaneously. In the case of humanitarian relief camps, containerized Schools could be purpose-built to meet the requirement of this process.

CHAPTER V: THE EFFECT OF FLY ASH ON SIMULATED HUMAN FAECES

With the design and implementation of a laboratory that is capable of disease diagnosis and water compliance monitoring the design must also include adequate waste disposal. The waste disposal can be observed in two major categories, namely; medical waste disposal from disease diagnosis and wastewater disposal from the water compliance monitoring, which can be grouped together with human waste disposal from the laboratory operator or 'citizen scientist'. Low-cost alternatives to human waste processing were investigated and a quantitative analysis was performed on the effect of fly ash on simulated human faeces. Fly ash has previously been used as a pit latrine additive to decrease pathogenicity of faeces and as a sorbent binding elemental species. The simulate faeces developed by Wignarajah and Litwiller (2006) have similar physical and chemical properties to real faeces and have been used primarily in anaerobic digestion studies. No studies have been performed to determine the effect of fly ash on simulated faeces used which is where the novelty lies; this allows for the determination of the effect of fly ash on the chemical, microbial and physical properties of faeces of standard, known properties, which allows for exact replicability in future studies. A leachate study was performed to determine the effect of fly ash on the microbial concentrations and the bioavailability and mobilization of bound elemental species.

5.1. INTRODUCTION

5.1.1. BACKGROUND

The laboratories design requires a laboratory operator to fulfil the purpose of the placement; due to the decentralized placement of the laboratory the operator is expected to reside within the container in which the laboratory is built. In the design of the laboratory the needs of the operator were taken into account, one of the primary needs is adequate provision of water and sanitation. The source of water will vary based on the placement of the laboratory; either from local catchments, rainwater harvesting or a borehole. The water acquired will serve the purpose of the occupants' potable water needs as well as sanitation; with a shower and basin. However, in a decentralized area it becomes increasingly more difficult to provide water for the use of a flush-toilet and, more importantly, the lack of infrastructure make it challenging to dispose of human waste in the traditional manner.

5.1.1.1. SANITATION: A GLOBAL PROBLEM

The Millennium Development Goal 7C was "halve the proportion of people without access sustainable to safe drinking water and basic sanitation by 2015" (Kamepalli and Pattanayak, 2015). The goal for access to drinking water was achieved by 2015 but the target for access to basic sanitation was not achieved (Carlson *et al*., 2016). Although improved sanitation has been achieved for 68 % of the world population, there are still 2.4 billion people without access to improved sanitation, in which 946 million people still defecating openly (World Health Organization and UNICEF, 2012). Carlson *et al*. (2016) identifies the lack of improvement due to stakeholders' failure to recognize sanitation as a higher priority; with drinking water dominating focus of governments, municipalities and organisations. In fact it was predicted that a further 10 billion USD would be required to reach the MDG Target 7C (Cross and Morel, 2005). Montgomery and Elimelech, (2007), identify improving sanitation and drinking water as the most effective and least expensive means of reducing fatalities and increasing public health (Montgomery and Elimelech, 2007). Moving forward, low-cost human waste processing solutions are imperative to the provision of sanitation in developing countries. The scope of this chapter is therefore not isolated to the laboratory operator but has applicability to the management of human waste. Additionally, the use of simulated faeces provides a unique perspective for future human waste processing studies. An ideal approach would treat human waste on-site without requiring power or water and allowing for safe disposal. For the purpose of this chapter single household use systems (1 to 10 people) were investigated because the primary purpose was to provide for a single laboratory operator. The quantity of faeces excreted by one person per day is between 70 and 520 g (wet weight) (Torondel, 2010); for the purpose of this chapter substantially less volumes of simulated faeces will be used to act as a proof of concept.

5.1.2. HUMAN WASTE DISPOSAL

As per operation of the mobile laboratory there is a full-time laboratory operator needed. This calls for a solution to the biological waste disposal needs of the human operator. The nano-membrane toilet developed by Parker and colleagues (2015) at Cranfield University is the most advanced UDDT. The toilet provides on-site treatment of human waste without water and power and can treat up to 10 peoples' waste (Parker *et al.*, 2015). The battery system used requires replenishment and the nano-membrane cartridges need to be changed once a month (Parker *et al.*, 2015). The technologies mentioned here and in chapter 1 provide good waste neutralization efficacy and disposal methods although they are expensive and require regular maintenance, this is especially pertinent when considering the waste disposal needs of only one person. The by-products are not re-usable which increases the environmental 'foot-print' of the waste disposal system, this is particularly important in the Eco-Lab design. For this, an ecological sanitation approach should be considered. The benefits of ecological sanitation include an overall increase in sanitation and health; the recycling and reuse of valuable nutrients that would otherwise be lost and increased soil fertility (Nordin *et al.*, 2013). In order for an ecological sanitation technique to be effective the reduction of pathogens to within limits and stability of organic matter requires consideration (Magri *et al.*, 2013). There is currently no unified method of adequately, inexpensively and safely disposing of human faeces. Although the Urine-diverting dry toilet has the capability to reduce faeces to dry matter, there is still concern about the chemical composition and pathogenicity of the dried faeces. Magri *et al*. (2015) achieved treatment of the faeces from a UDDT with the use of fly ash, limestone and urea. The addition of fly ash and limestone reduces the pathogenicity of faeces by increasing the alkalinity and the urea increases the ammonia concentration (Magri *et al*., 2015). The bacterial species commonly associated with faecal matter cannot survive in the strong alkaline conditions created by the additives (Nordin *et al*., 2009). Magri *et al*. (2015) achieved a 3-log reduction of faecally-associated bacteria in 30 days and phages in 44 days (Magri *et al*., 2015).

5.1.2.1. USE OF FLY ASH

Fly ash is produced during the process of burning coal; large amounts are formed concomitantly by the operation of coal dependent power plants (Phukan and Bhattacharyya, 2003). Approximately 600 million tonnes of coal is utilized annually in the production of power concomitantly producing approximately 500 million tonnes of fly ash. With the world average of fly reuse of 16 %, ranging from 3 to 57 % reuse, there should be better utilization of the abundant resource (R.C. Joshi, R.P. Lothia 1997). Additionally, fly ash is considered an environmental contaminant because of the toxic elements formed in its structure during the combustion process. The majority of fly ash produced is disposed of in landfills, which due to the toxicity of some of the elements associated, can cause environmental concerns (Ahmaruzzaman, 2010). Ahmaruzzaman (2010) suggests that because of this, the cost of disposal will be ever-increasing due to environmental risk and the fines associated with this- also suggesting that it may be prohibited altogether. Fly ash often contains essential elements for plant growth such as the micronutrients: zinc, iron, copper, manganese, boron; and macronutrients: phosphate, potassium, calcium and magnesium (Ahmaruzzaman, 2010). The composition of which is highly dependent on the source of coal and the way in which collection was performed (Pandey and Singh, 2010). Fly ash has a distinct agricultural use and aids in soil fertility by increasing the soils ability to maintain a high moisture content; it has also been used as a form of zeolite to remove heavy metals from water (Naik *et al*., 2009). Weng and Huang, 1994, showed the ability of fly ash to remove heavy metals, while other literature showed its ability to decrease turbidity, flouride and COD in wastewater (Banerjee *et al*., 1997a; Naik *et al*., 2009). It has also been shown to decrease phenolic compounds (Kao *et al*., 2000). Banerjee *et al*. (1989), showed the ability of fly ash to act as a sorbent to bind to and precipitate the aromatic hydrocarbon o-xylene (Banerjee *et al*., 1989), whilst the adsorption of oxalic acid from solution was performed by Jain *et al*. (1980), with the adsorption kinetics following the Langmuir isotherm (Jain *et al*., 1980). Banerjee later found the applicability of fly ash in the removal of aldehydes, alcohols, ketones and aromatics (Banerjee *et al*., 1997b). Hung (1983) showed higher removal of aromatic compounds in comparison to aldehydes, alcohols and ketones in an adsorption study in an aqueous solution (Hung, 1983); with 30 to 58 % removal of total organic carbon which was directly correlated to the fly ash concentration used and inversely correlated to the fly ash particle size (Ahmaruzzaman, 2010; Hung, 1983). Based on these findings, the immobilization of organics in an aqueous solution is promising (Ahmaruzzaman, 2010). Additionally, due to the aluminium, iron, calcium, and silica oxides present in fly ash and the affinity of these oxides to adsorb to phosphates there is great potential for phosphate precipitation with the use of fly ash (Ahmaruzzaman, 2010).

5.1.3. SIMULATED HUMAN FAECES

Wignarajah and Litwiller (2006) optimized the composition of synthetic faeces to match the chemical and physical properties, simulate water retention and consistency of real faeces (Wignarajah *et al*., 2006). The optimized formulation was used in the design of an anaerobic digester for waste disposal and fuel production by Dhoble and Pullammanappallil (2014); the synthetic faeces showed similar characteristics to real faeces and demonstrated feasible digestion dynamics (Dhoble and Pullammanappallil, 2014). Similarly, Colón *et al*. (2013) used the simulated faces for anaerobic digestion with the biogas produced being utilized for pathogen sterilization (Colón *et al*., 2013). The heat sterilization system developed showed high removal of Chemical Oxygen Demand (COD) and greater than 7 log reduction in *E.coli*. Using simulated faeces has range of benefits; they are not as hazardous to handle as the bacterial content is controlled; the composition is constant unlike real faeces, so the exact effect of changing one parameter can be observed. Additionally, the

simulated faeces have comparable properties to real faeces and have been used in several studies which allows for inter-study comparison.
A comparison between the simulated faeces and real faeces is shown in Table 5.1. The chemical compounds used in the synthesis of the simulated faeces are: cellulose acetate, polyethylene glycol (PEG), peanut oil (oleic acid), Psyllium powder, Miso (Soya), inorganics (KCl, NaCl and CaCl2) and dried coarse vegetable matter (Wignarajah *et al.*, 2006).

Table 5.1. Comparison between simulated faeces and real human faeces

Property	Simulated feaces	Real faeces
Moisture (%)	80	65-85 (Wignarajah *et al.* 2006)
TS (%)	20	15-35 (Wignarajah *et al.* 2006)
COD (g COD/g TS)	1.23	1.24 (Jönson *et al.*, 2005)
CODs (g COD/g TS)*	0.85	-
CODdis (g COD/g TS)*	0.38	-
Ntot (% dry matter)	2.55	2-3 (Barman *et al.*, 2009)
N-NH3 (% Ntot)	3.02	-
pH (1:5 w:v)	5.30	4.6-8.4
Coduct. (1:5 w:v, mS/cm)	5.7	-

* CODs = COD of solids fraction. * CODdis = COD dissolved.

Cellulose acetate (CA) was used instead of cellulose because of the varying reactivity of cellulose powder from different sources. Cellulose is a polysaccharide consisting of β(1-4) glycosidic bonded D-glucose monomers (Crawford, 1981); the introduction of the acetate to form the cellulose acetate ester increases the solubility of cellulose in water which is otherwise insoluble (Krumm *et al.*, 2016). Cellulose has several reactive hydroxyl groups may donate an electron to form partial or full bonds with other molecules. Polyethelene glycol (PEG) is a polymer composed of ethylene oxide monomers, which is highly soluble in water. In the presence of alkaline catalysts the anionic polymerization reaction mechanism is favoured which produces PEG with uniform dispersity. More consistent adsorption dynamics are observed with the increase in uniform dispersity. Peanut oil is primarily composed of fatty acids: the monounsaturated omega-9 fatty, oleic acid (46.8 %); the polyunsaturated omega-6, linoleic acid (33.4 %) and the monounsturated, palmitic acid (10.0 %) (Gebhardt *et al.*, 2007). The fatty acids have the ability to donate a hydrogen ion in solution creating a reactive negatively charge hydroxyl group (–OH) however there is low water solubility at neutral pH. Psyllium husk powder is produced by grinding seeds of the plant *Plantago ovate*. The powder is hygroscopic and shows the high adsorption to water molecules; the soluble fraction in psyllium is the hemicellulose, arabinoxylan consisting of 22.6 % arabinose and 74.6 % xylose (Fischer *et al.*, 2004). Miso paste is produced with the fermentation of soybeans with aid of the Aspergillus oryzae fungi; it is primarily composed of phenolic acids ferulic, p-coumaric, syringic, vanillic, daidzein, genistein and p-hydroxybenzoic acid (Farnworth, 2003). Calcium carbonate was used to simulate the inorganic fraction in human faeces due to the low water solubility (Brečević and Nielsen, 1989). Due the monitoring of phosphate in the leachate, the ability of calcium carbonate to adsorb phosphate should be noted (Lieberman *et al.*, 1989).

5.1.4. LEACHATE STUDIES

The inadequate management of faecal matter can lead to pollution of water bodies; the mode of contamination can be directly via surface water or indirectly via the groundwater table. In rural areas, water supply is accessed via the surface waters or the groundwater supply by boreholes, which causes sanitation concerns. Aside from the sanitation concerns from faecal contamination of these sources, there can also be large quantities of organics in the water supply, which causes eutrophication in surface water bodies. The increase in turbidity and microbial contamination in water sources is directly correlated with rainfall (Auld *et al.*, 2004). The increase in rainfall has in some areas caused inefficiencies in water treatment facilities ability to decrease microbial quantities due to the increases turbidity which, has resulted in a concomitant increase in waterborne disease outbreaks (Auld *et al.*, 2004; Hrudey *et al.*, 2003). A leaching study will determine the effect of fly ash on the mobilisation, bioavailibilty and pathogenicity of simulated faeces. The reduction of indicator organisms and the availibility of phosphate, nitrates and ammonia for uptake by plants and the leaching of chlorides and sulfates into the groundwater table. As previously mentioned, fly ash has been shown to decrease COD in wastwater and the COD will be measured in the water leached from the simulated faeces will be of particular interest. Additionally, fly ash may leach potentially toxic elements that are water-soluble; this creates a secondary environmental pollution problem. According to Elseewi *et al*. (1980) between 1 and 3 % of fly ash constituents are water-soluble; the most common leached cationic constituents were calcium and sodium and calcium hydroxide and hydroxide ions were the most common cationic compounds (Elseewi *et al*., 1980). The solubility and mobilization of elements were dependent primarily on the alkalinity of the leachate and the calcium fraction present in the fly ash (Eisenberg *et al*., 1986).

5.2. METHODOLOGY

5.2.1. MATERIALS

The fly ash used was obtained from SAPPI, Mandeni, RSA. The components of the simulated faeces were: polyethylene glycol from Saarchem (Pty.) Ltd. (Muldersdrift, RSA); calcium carbonate and cellulose acetate from Minema Chemicals (Pty.) Ltd. (Johannesburg, RSA); psyllium husk; peanut oil (oliec acid) and miso paste were acquired from Fusion Speciality Food Shop (Grahamstown, RSA). The dried vegetable matter was obtained from St. Andrews College kitchen. Coarse sand was acquired from Penny Pinchers (Grahamstown, RSA). The following Spectroquant® test kits were acquired from Merck (Pty.) Ltd. (Johannesburg/Cape Town, RSA). The COD (Chemical oxygen demand) cell test (catalogue number: 1145400001; range 10 – 150 mg/l), Nitrate cell test (catalogue number: 1145630001; range 0.5 – 25.0 mg/l and 2.2 – 110.7 mg/l), Phosphate test (catalogue number: 1148480001), Ammonium cell test (catalogue number: 1147390001; range 0.010 – 2.000 mg/l and 0.1 – 2.58 mg/l), Sulphate test (catalogue number: 1147910001; range 25 – 300 mg/l) and Chloride test (catalogue number: 1148970001; range 2.5 – 250 mg/l). The m-FC agar and the Tryptic Soy broth were acquired from Merck (Pty.) Ltd.

(Johannesburg/Cape Town, RSA) and Sigma Aldrich (Pty.) Ltd. (Johannesburg, RSA) respectively.

5.2.2. FLY ASH CHARACTERISTICS

Fly ash was characterised by an analysis for metals by ChemTech laboratory services using EPA Method 200.7. X-Ray Diffraction (XRD) was performed using a Shimadzu LabX XRD-6100 X-ray Diffractometer and the mineral content was determined by the National Innovation Center for Nanotechnology, Department of Chemistry, Rhodes University.

5.2.4. LEACHATE PROTOCOL

The simulated faeces were prepared according to Appendix B and the method by Wignarajah (2006) with the replacement of 30 g of ***E.coli*** with the equivalent of sterilized sand and the addition 3 ml of 10th gen inoculated Tryptic Soy broth (Wignarajah ***et al.***, 2006) Cellulose was replace with cellulose acetate of the same mass. Fly ash (1 g) was added to 1, 2, 5 and 10 g of simulated faeces (with and without inoculation) and the resultant mixture was leached in deionized water for 1 and 24 hours on an orbital shaker (Model) for 24 hours at 100 rpm. Nitrate, phosphate, ammonia, sulfate, chloride and COD were determined in leachate before and after leaching periods with the respective Spectroquant® test kits. Turbidity, pH and faecal coliforms present were determined after the leachate periods. Faecal coliforms were expressed as Colony forming units per 100 ml (CFU/100 ml). All samples were performed in triplicate and the mean results for each test was reported.

5.2.2. MICROBIAL ANALYSIS

Faecal coliforms were enumerated from a leachate samples with spread-plating on m-FC agar under sterile technique. Isolated colonies were cultured in Tryptic Soy broth for ten 48-hour generations. Faecal coliform enumeration was performed on m-FC agar at 44.5 °C for 24 hours. The m-FC agar and Tryptic soy broth were prepared by dissolving 52 g and 30 g (dehydrated m-FC and Tryptic media respectively) in 1000 mL of deionised water whilst boiling for 1 minute. The agar and broth medias were autoclaved for 15 minutes at 121 °C in 1 L

Schott bottles (Labotec, Midrand, South Africa) the with the RAU-53Bd REX MED autoclave (Hirayama Manufacturing, Tokyo, Japan). The m-FC agar was prepared in sterile plastic Petri dishes from EC Labs (Port Elizabeth, RSA). Samples were inoculated onto plates and colonies inoculated from plates to broth using sterile technique in a LA1200 BII laminar-flow hood. The 37.5 °C incubations took place in the Labcon low temperature incubator LTIE 10 (Labmark, Johannesburg, South Africa) and the 44.5 °C incubations were performed in the Heraeus Model FT 420 incubator (Heraeus Kulzer GmbH, Dormagen, Germany).

5.2.3. PHYSIOCHEMICAL ANALYSIS

The leachate from the fly ash and faeces studies was analysed for nitrate (NO_3^-), phosphate (PO_4^{3-}), ammonium (NH_4^+), sulfate (SO_4^{2-}), chloride (Cl^-) and COD using the respective Spectroquant® test kits. Spectrophotometric measurements were determined with the Shimadzu 1200 UV/VIS spectrophotometer (Shimadzu, Johannesburg, South Africa). The pH and Turbidity was determined using the pH meter from Hannah Instruments (Port Elizabeth, South Africa) and the Lutron TU-2016 portable turbidimeter from Test and Measurement Instruments CC (Johannesburg, South Africa). All quantitative analysis was performed according to Standard Methods (Clesceri *et al.*, 1998).

5.3. RESULTS AND DISCUSSION

5.3.1. FLY ASH CHARACTERISTICS

Due to the variable compostition of fly ash depending on the source and the method of collection shown by Pandey and Singh (2010), the exact composition of the fly ash used requires characterization. The mineral composition of fly ash is dependent on the geological conditions under which the coal was diposed and the temperature and environmental conditions under which combustion took place. Ahmaruzzaman (2010) describes the mineral compostion of fly ash characterized by X-ray diffraction (XRD) as predominantly quartz, ilite, sideraete and kaolinite; with less recurrent minerals: pyrite, calcite and hematite. The major crystalline components in low calcium fly ash are quartz and mullite and quartz, tricalcuim aluminate, calcium silicate and tetracalcium aluminosilicate making up the crystalline sturture of high calcium fly ash (Ahmaruzzaman, 2010). Fly ash elemental and mineral content was determined by XRD performed by ChemTech laboratory services. Table 5.1. shows the metals that were presnt in order of concentration.

Table 5.2. Metals present in fly ash characterized by XRD analysis

Element	Detection Limit (mg/L)	Concentration (mg/L)
Ca	0.009	4165.46 ± 81.03
Al	0.003	2069.82 ± 81.63
Mg	0.001	468.81 ± 12.66
Fe	0.004	387.37 ± 24.78
Sr	0.001	77.18 ± 1.86
Na	0.009	31.42 ± 2.62
Cu	0.001	1.59 ± 0.12
Ba	0.001	1.51 ± 0.10
Ni	0.001	0.96 ± 0.04
Cd	0.001	< 0.001
Pb	0.001	< 0.001

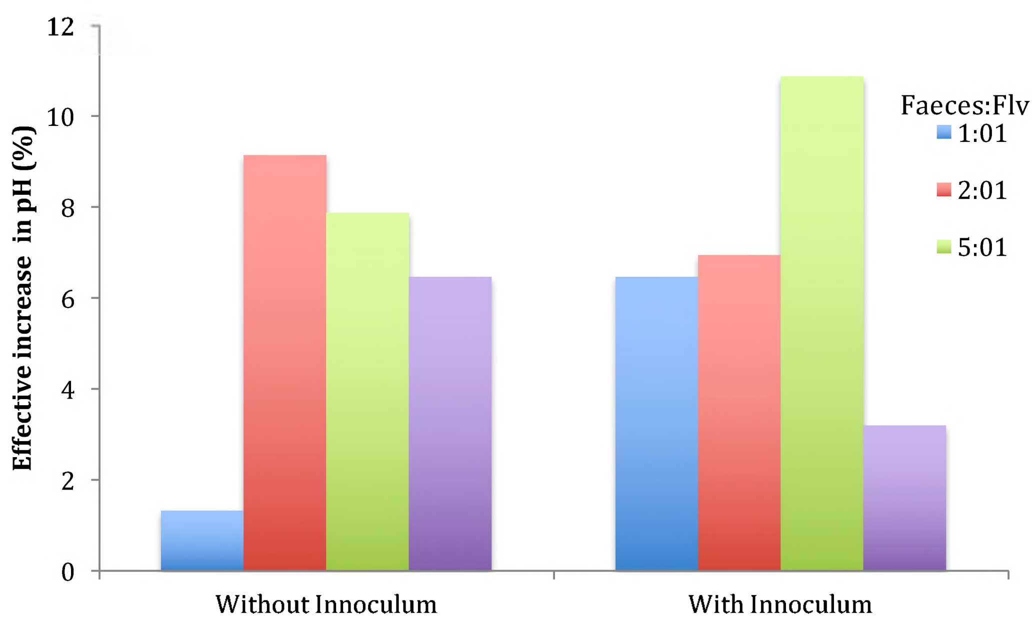
The metals that were present in the highest concentration were aluminium and calcium with 2000 and 4000 mg/L respectively; significant concentrations of magnesium and iron were observed with the remianing metals present in lower concentrations. Cadmium and lead were below the detection threshold. The crystaline structure of fly ash was primarily made of up mullite and quartz making up 72 and 27 % of the sample respectively. Trace elements of lime were also detected. Mullite and quartz contain large amounts of aluminium, silicon and calcium, so fly ash is expected to also contain elemental silicon. Based on the classification preformed by the American Society for Testing Materials (ASTM), the fly ash used falls in 'Class F' due to the high calcium, aluminum and iron content and the greater prescence of mullite and absence of lime. Class F fly ash is produced by burning pozzolanic coals such as bituminous or anthracitic coal and the calcium is primarily bound to alumina and silica in the form of calcium hydroxide or calcium sulphate. The prescence of the alkaline salts give Class F fly ash high akalinity which is of particular interest as an antimicrobial.

5.3.2. THE EFFECT OF FLY ASH ON SIMULATED HUMAN FAECES

A simulated faeces equivalent developed by Wignarajah and colleagues (2006) was used to test the applicability of fly ash to treat faeces. The simulated faeces were modified from Wignarajah and colleagues (2006) and the composition is listed in Table 5.1. The results that were found to be significant are shown in this section; the full set of results is detailed in Appendix B.

5.3.2.1. PHYSICAL PROPERTIES

The addition of fly ash was expected to have an effect on the pH and turbidity of the leachate; the pH was expected to become more basic over time and the turbidity was expected to decrease based on findings by Magri ***et al.*** (2013). The effective increase in pH over 24 hours is displayed as percentages in Fig. 5.1. The effective increase was calculated by subtracting the change pH in experimental sample from the control sample; which contained 1 g of faeces without the addition of fly ash.



<u>Figure 5.1. The effect of 1 g of fly ash on the pH of the leachate over 24 hours</u>

In all samples there was and effective increase in alkalinity over the 24-hour period. A constant quantity of fly ash added; there was a greater increase in alkalinity shown in the samples with 2 and 5 g of simulated faeces (for both the inoculated and non-inoculated samples). The highest percentage increase in pH was shown in inoculated sample with 5 g of faeces; the 12 % effective increase in pH was shown with the increase in pH from 6.8 to 8.4. A pH of 12.2 was observed in human faecal sludge after 14 days by Pichtel and Hayes, (1990) and a pH 13 in wastewater after 30 days by Magri *et al.* (2015) (Magri *et al.*, 2015; Pichtel and Hayes, 1990), indicating that the pH will continue to increase after 24 hours. The increase in pH could be responsible for the reduction in faecal coliforms shown in Fig. 5.5. by the alkaline hydrolysis mechanism. According to Magri *et al.* (2013), fly ash can act bind to and precipitate organic matter thereby decrease turbidity; Naik *et al.* (2009) showed a decrease in turbidity in wastewater with the addition of fly ash (Naik *et al.*, 2009). The effective decrease in turbidity over 24 hours is displayed as percentages in Fig. 5.2. The effective decrease was calculated by subtracting the percentage change in each experimental sample from the percentage change in the control; which contained 1 g of faeces without the addition of fly ash.

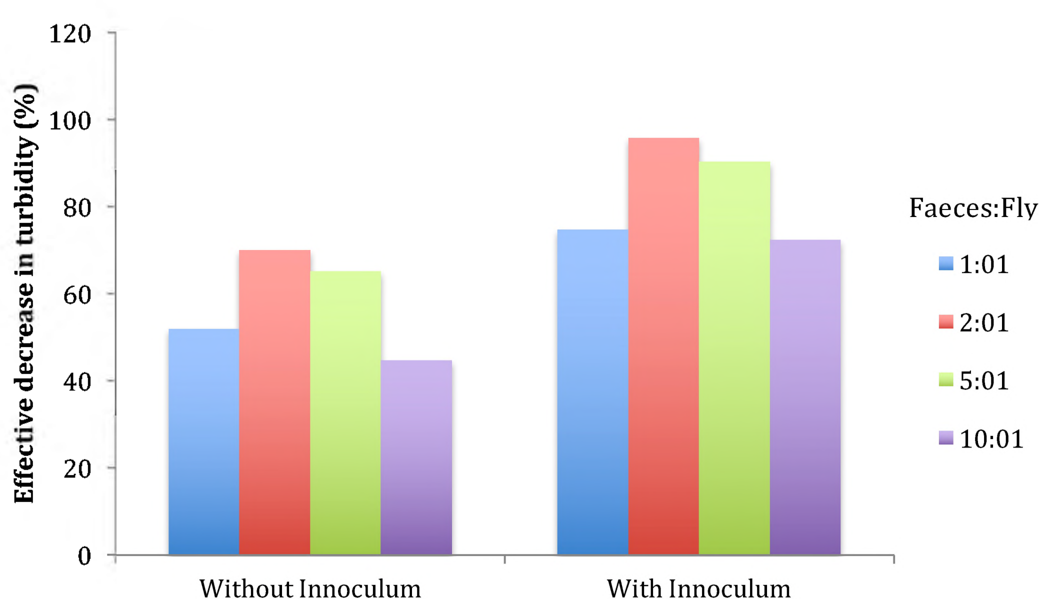


Figure 5.2. The effect of 1 g of fly ash on the turbidity of the leachate over 24 hours

In each of the samples an effective decrease in turbidity was shown, with largest decrease shown in the 2:1 (Faeces:Fly ash) sample which displayed 95 % and 70 % reduction in turbidity in the inoculated and non-inoculated samples respectively. The least effect on turbidity by fly ash shown with in the samples with 10 g of simulated faeces, although a decrease was still shown, this is due to the small amount of fly ash per faeces. The samples that were inoculated with faeces are displayed as having an overall higher turbidity removal; this is mainly due to the higher turbidity of the control sample containing bacteria, which showed an increase in turbidity over the 24 hours due to bacterial growth and death. The difference in turbidity between the control sample and the fly ash samples was far more significant than the difference for the un-inoculated control and experimental. A similar overall trend is shown in the samples with and without inoculum; based on the findings, the optimum removal of turbidity is shown at a ratio of 1 g of fly ash per 2 g of faeces.

5.3.2.2. CHEMICAL PROPERTIES

The use of fly ash has previously shown efficacy in the removal of heavy metals and organics from wastewater (Ahmaruzzaman, 2010). Chemical oxygen demand (COD) was used as an indirect measure of organics for the simulated faeces and fly ash leachate study. Organic compounds have been shown to be present in fly ash particles; which are dependent primarily on the source of combustion. Some of the organics in fly ash are known mutagens; which can release unstable complexes formed with chloride, sulfate, sulfide, and carbonate ions when leached. The creation of artificial unstable minerals can also occur; such as nitrates, calcium oxalate and oxyhydroxides. The most common components of fly ash formed at high temperatures are alumino-silicates and salts including oxides, sulphates and chlorides (Gitari ***et al***., 2006). Due to the instability of some of the complexes they may be highly soluble in water. The mobilization and solubility of these species is largely dependent on the source of fly ash and the compound with which it is leached; the lack of solubility is due to the organics being incorporated into other inorganic compounds- which precipitate in solution (Ahmaruzzaman, 2010). The concentration of these constituents in the leachate will therefore determine the solubility (Ahmaruzzaman, 2010). According to Murayama ***et al***., (2003) fly ash can act as a zeolite by precipitating phosphate from wastewater; additionally simultaneous removal of ammonium was shown (Murayama *et al*., 2003). Similarly, Zhang *et al*., (2007) showed the simultaneous removal of low concentrations of ammonium and phosphate ions in real effluent (Zhang *et al*., 2007). Based on the literature reviewed the chemical constituents selected for quantification in the leachate were: nitrate; ammonium; phosphate; sulphate, chloride and COD as a measure of total organics. An increase in sulphate, chloride and nitrate over 24 hours would indicate that the ions were solubilized in water from fly ash or the simulated faeces; conversely, a decrease would indicate the formation of recalcitrant inorganic complexes- the change in chemical structure indicates their solubility and bioavailability. Inversely, the decrease in phosphate and ammonium ion concentrations in the leachate after 24 hours indicates the adsorption kinetics of the fly ash and the resultant zeolite formation- the increase in concentration suggests that these ions were found in soluble form in the simulated faeces. The composition of un-inoculated sample is detailed in the methodology; the concentrations of each chemical constituent was quantified in the leachate after 1 and 24 hours of leaching- the results are shown as percentage change in Fig. 5.3.

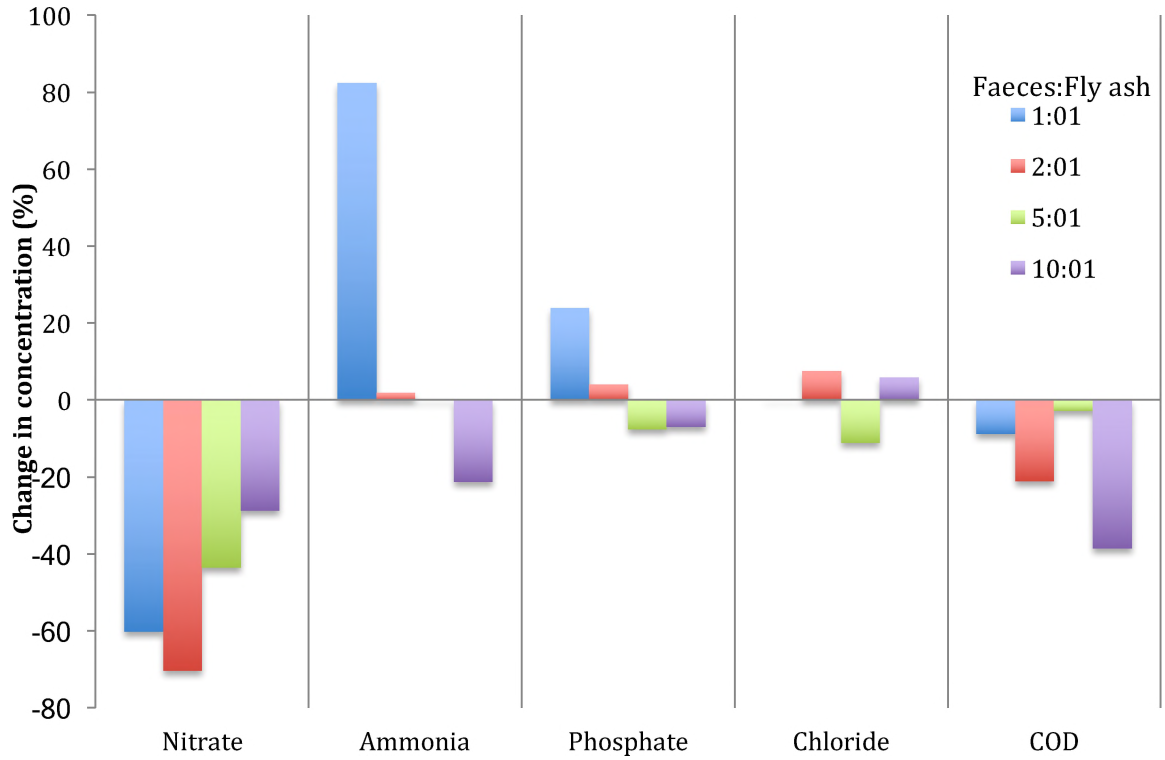


Figure 5.3. Percentage change in concentration of chemical constituents over 24 hours in the un-inoculated sample

There was a substantial decrease in nitrate concentrations for all concentrations with the highest percentage decrease of 70 % in the sample with 2 g faeces to 1 g fly ash. The decrease in nitrates indicates the formation of inorganic matrices incorporating nitrate; for confirmation and to determine the exact dissolution kinetics a further leachate study should be performed with 40 % hydrogen peroxide, nitric acid or benzene as shown by Ahmaruzzaman (2010). The most substantial increase in concentration in ammonia and phosphate was shown in the 1:1 sample with 83 and 24 % respectively; this indicates that these ions were solubilized from the simulated faeces in water. Furthermore, there was a direct correlation between ammonium and phosphate concentrations and the amount of faeces added (shown in Appendix B), which confirms the solubility of these ions from the simulated faeces. In the 5:1 and 10:1 samples the concentrations of ammonium and phosphate were shown to decrease; this could be due to the higher concentrations being adsorbed by fly ash in the formation of zeolites. The chloride concentrations were relatively low for all samples before and after the 24-hour leaching period with the largest percentage change shown in the 5:1 sample with 11 % decrease representing the difference between 0.18 and 0.16 mg/L. The XRD analysis did not identify chloride in the fly ash examined, the source of chloride could have been in undetectable amounts in fly ash or it could have been solubilized from the simulated faeces; miso paste has been shown to contain relatively high chloride concentrations in the form of soluble something chloride. The organics in the leachate were shown to decrease over the 24 hour period with 38 % removal shown in the sample with 10:1 faeces to fly ash. With the exception of the 5:1 sample there was a correlation between the mass of faeces used and the removal percentage of organics indicating that the binding mechanism between fly ash and organics was dependent on concentration of faeces. The decreased organics could be due the sorption of aromatic sugars xylose and arabinose from psyllium husk by fly ash. The levels were below the detection limit and are not shown in Fig. 5.3. (shown in Appendix B). The composition of the inoculated sample included 3 mL of 10^{th} generation tryptic soy broth added to 100 g of freshly prepared simulated faeces. The concentrations of each chemical constituent in the leachate was quantified after 24 hours of leaching; the results are shown in Fig. 5.4. (below) as percentage change in concentration.

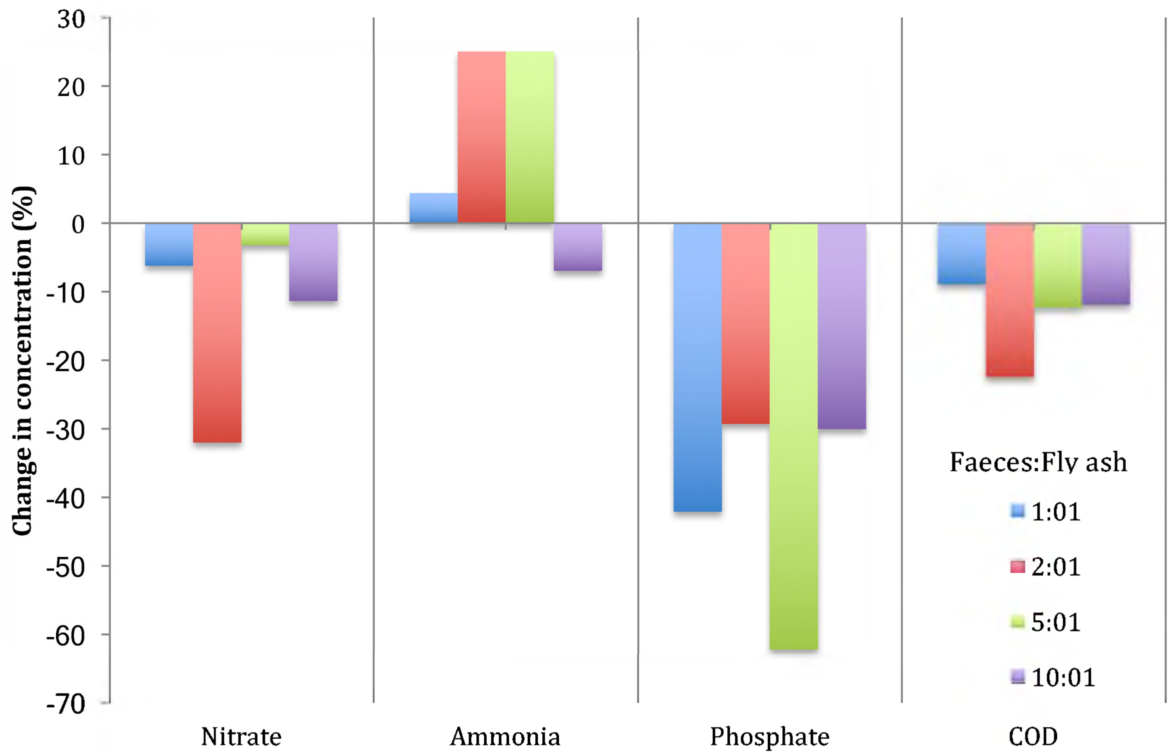


Figure 5.4. Percentage change in concentration of chemical constituents over 24 hours in the inoculated sample

The nitrate concentration was shown to decrease in the leachate over the 24-hour period, which matches the trend shown by the un-inoculated sample and similarly the maximum removal percentage was shown in the 2:1 sample; this may indicate the formation of inorganic matrices as previously mentioned. The percentage concentration change trend in ammonium and phosphate was clearer than in the un-inoculated sample, with ammonia concentration increasing and a substantial percentage decrease in phosphate concentration shown. The substantial decrease in phosphate concentration may be due the fly ash acting as an adsorbent and precipitating phosphate. The 29 and 30 % removal of phosphate in the 2:1 and 10:1 faeces:fly ash samples is similar to the 10–32 % phosphate uptake shown with calcium-rich fly ash (Vordonis *et al.*, 1988). The fly ash was categorized as Class F based on the calcium and iron content determined by the XRD analysis. The results are therefore similar to the findings of Chen *et al.* (2007). Chen *et al.* (2007) found a direct correlation between the sorption of phosphate to fly ash and the total calcium and iron concentrations of the fly ash; which is in line with the results obtained (Chen *et al.*, 2007). Furthermore, greater phosphate removal was shown at higher pH levels and loose binding of the immobilized phosphate to fly ash was observed (Chen *et al.*, 2007). This is important for the reuse of the precipitant formed in agriculture, as the phosphate will be more readily available to be utilized by plants. The decrease in phosphate could also have been due the adsorption of phosphate to calcium carbonate with the calcium phosphate co-precipitant formation occurring; this was shown at with low phosphate concentrations by Yagi and Fukushi (2012). An XRD analysis on the fly ash and faeces combination is required to determine the exact mechanism of phosphate removal. No significant sorption of the ammonium ions was observed and the ammonium concentration was shown to increase over the 24-hour period. The increase in ammonia can be associated with the solubilizable fraction in the choline and riboflavin in the miso paste dissociating in water and may be associated with the increased alkalinity. An overall decrease in organics was shown in all inoculated samples with the highest percentage removal shown in the 2:1 sample. The removal of organics can be attributed to the adsorption of the phenol acids in the miso paste to fly ash as shown by Kao *et al.* (2000). Chloride was not shown because there was no change in concentration over the 24-hour period and sulphate concentration was emitted because the values were below the detection limit; the omitted results are shown in Appendix B.

5.3.2.2. MICROBIAL PROPERTIES

To the simulated faeces named the 'inoculated sample' 3 mL of 10th generation tryptic soy broth was added to the 100 g. The faecal coliforms in the leachate were enumerated on m-FC agar after 1 hour and 24 hours leaching. In the samples containing fly ash there was completed removal of faecal coliforms after 24 hours. The initial faecal contamination in the leachate after 1 hour is shown in terms of CFU per mL in Fig. 5.5.

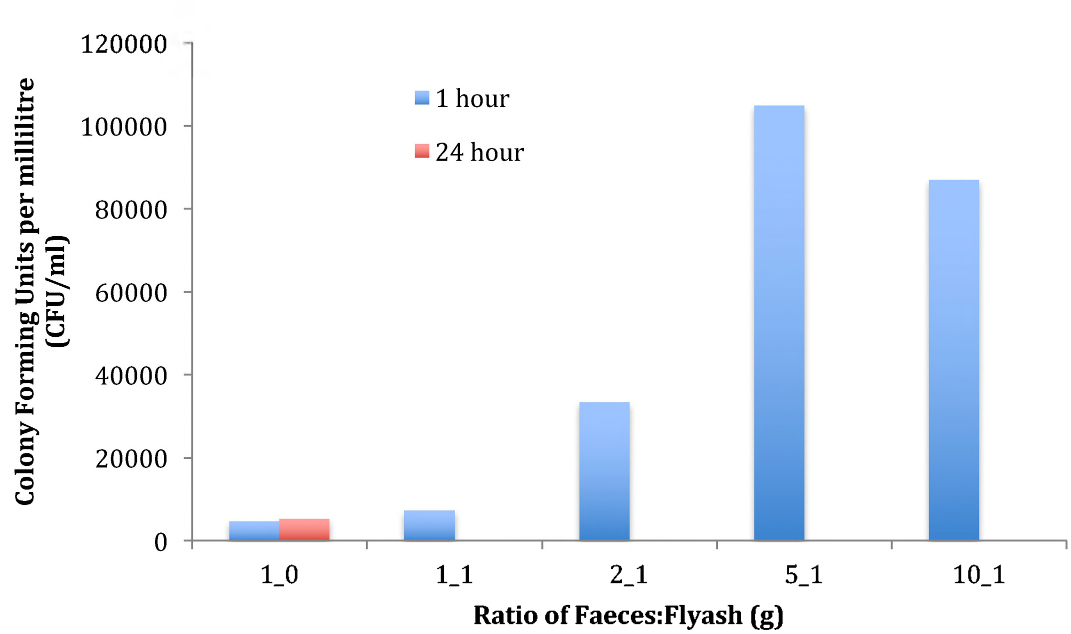


Figure 5.5. The CFU/mL in the respective simulated faeces after leaching for 1 hour

There was a direct correlation between the faecal coliforms enumerated and the mass of faeces added to each sample indicating that the bacterial inoculation in the simulated faeces was successful. The sample containing 1 g of faeces and no fly ash showed an increase of 721 CFU/mL over the 24-hour period; whilst all samples containing fly ash showed complete faecal coliform removal indicating that fly ash had a sterilization effect. It was shown by Magri *et al.* (2015) and Nordin *et al.* (2009) that an increase in alkalinity associated with the addition of fly ash is responsible for sterilization by the mechanism of alkaline hydrolysis; a 3-log reduction in faceal coliforms was shown by Magri *et al.* which is similar to the 5-log reduction shown in the 5 to 1 sample. The decrease quantity of CFU/mL in the 10 as 1 sample compared to the 5 to 1 sample after 1 hour could be due the growth kinetics of the faecal coliforms; the increased quantity of bacteria could have exhausted the growth substrate resulting in the stationary and subsequent death phase occurring. The minimum growth observed in the 1 g faeces with no fly ash may have been due to a similar reason. The suspected sterilization mechanism of alkaline hydrolysis is a nucleophilic substitution reaction that occurs under strong alkaline conditions where a hydroxide ion acts as the attacking nucleophile. According to Vonderwell *et al.* (2015), the sterilization of bacteria by alkaline hydrolysis occurs at pH 8 and up with temperature under 100 °C and normal atmospheric pressure (Vonderwell *et al.*, 2015).

There were no coliforms observed in the leachate studies performed with un-inoculated simulated faeces; which shows that the controlled inoculation of simulated faeces for simulation purposes is feasible and can be used for microbial and physiochemical analysis of different treatment technologies.

5.4. CONCLUSION

The novel use of simulated faeces to quantify the efficacy of fly ash as a low-cost human waste processing system showed promising results. After the leachate protocol there was an increase in alkalinity and decrease in turbidity observed; 100 % sterilization was displayed in all samples indicating an alkaline hydrolysis mechanism.

The decrease in nitrate, phosphate and organics showed the applicability of fly ash to be used as a sorbent to bind to and precipitate these ions and organic contaminants. The effect of leaching of fly ash on ammonium, chloride and sulphate concentrations was unclear, indicating that the ammonium fraction was not precipitated by fly ash and the separation of sulphate and chloride (if present) was not shown from fly ash. The use of fly ash addresses the issues associated with inadequate disposal and the concomitant environmental concerns associated with it; additionally, there is wastewater treatment applicability and a fertility benefit with utilizing fly ash, which can be marketed as a necessary agricultural commodity. The use of fly ash to treat human faeces has practical significance for on-site human waste management with the mobile laboratory. The bacterial removal shown in the simulated faeces indicated the possibility of using fly ash to sterilize real faeces.

The simulated faeces have applicability to be used in place of real faeces for low-cost treatment methodologies; due to the standard composition and the characterized fly ash all methodologies performed have high reproducibility. In future studies the dissociation of bound elemental fractions should be investigated after leaching with a further leachate study being performed with hydrogen peroxide, nitric acid or benzene as the leachate solution; this will confirm the binding of these elemental species and their dissociation constant-which is important when considering uptake of these macronutrients by plants and the leaching into surface and groundwater supply.

The potential reuse of fly ash has been studied as a soil amendment; the applicability of fly ash-phosphate co-precipitant to enrich soil fertility remains relatively unexplored in literature. The leaching of elemental bound species could increase soil fertility and the properties of fly ash could aid in essential soil minerals.

Recommendations for future research are to assess the long-term leachability of a fly ash-faeces compound in soil and the possibility of this compound as a amendment and fertilizer.

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APPENDICES

APPENDIX A- Equipment selected

The following section details the characteristics of the equipment selected for incorporation in the mobile laboratory. The data was used in the simulation, optimization and modeling of the equipment detailed Chapter 4. The blocks shaded in red indicate the usage of power and the blocks shaded in green represent the production of power.

A.1. Power producing technology.

Purpose	Equipment	Model no.	Supplier	Dimensions (mm) L x W x H	Weight (kg)	Energy output	Total cost (Rand)
Energy producing	Power Pallet PP20	pp20	All Power Labs (California, USA)	1200 x 1200 x 1800	791	15 kW@50 Hz/18 kW@60 Hz	496 458.32
	Battery Bank (4/8)	Trojan T-105	Sustainable Inc. (Cape town, RSA)	724 x 276 x 264/ 724 x 552 x 264	112/124		10 656.00/ 21 312.00
	Inverter with Charger	Microcare 3kW 48V Bi-Directional Pure Sine		600 x 400 x 300	10		20 560.99
	PV panels (x25)	ReneSola Virtus II 250W		1640 x 949 x 40	18.5 (x 25)	250 W (x 25)	76 594.00
	Wind turbine	Kestrel e300i generator		850 x 610 x 410	70	1000 W	55 935.00
		Kestrel e300i blade set		1540 x 280 x 230	9		
		Kestrel e300i tailboom		1880 x 280 x 230	15		
		Kestrel e300i charge controller		350 x 260 x 180	6,5		
		Kestral e300i divert resistor		390 x 260 x 150	7,5		

A.2. Water treatment technology.

Purpose	Equipment	Model no.	Supplier	Dimensions (mm) L x W x H	Weight (kg)	Utility/Energy usage	Total cost (Rand)
Water treatment	Reverse Osmosis system	SW-1.3K425	Pure Aqua Inc. (California, USA)	1295 x 534 x 762	132	460V/3ph/60Hz	85 769.03
	Water Pump	HT V180F	Pumps for Africa Inc. (Johannesburg, RSA)	185 x 180 x 365	8.5	180 W	2029.20
	Water Storage tank	V5000S	JoJo tank Inc. (Pretoria, RSA)	1820 (diameter) x 2255 (height)	120	5000 L storage	5007.00

A.3. Waste disposal technology.

Purpose	Equipment	Model no.	Supplier	Dimensions (mm) L x W x H	Weight (kg)	Efficiency	Total cost (Rand)
Waste disposal	Gas-fired incinerator	M- L110-2	Littergon Inc. (Cape Town, RSA)	600 (diameter) x 1600 (height)	80	3.5 kg-5 kg/ hour/ 100 kg waste	36 608.00
	Gas cylinder (x4)		Afrox (Johannesburg, RSA)	350 (diameter) x 1300 (height)	48 (empty) 92 (full)		5790.00

A.4. Disease diagnosis technology

Purpose	Equipment	Supplier	Model no.	Dimensions (mm) L x W x H	Weight (kg)	Energy output/usage (W)	Total cost (Rand)
Disease diagnosis	TwistDx Twirla™	TwistDx Inc. (Cambridge, UK)	Twirla™	560 x 390 x 610 (size of storage unit)	4 + 6 10	5v/2A micro USB Power supply (NiMH batteries)	4972.93
	TwistAmp®exo+Campylobacter		TAEXOCAMP01			N/A	7492.24 (96)
	TwistAmp nfo, lateral flow DNA detection*		TANFO01KIT			N/A	6046.25 (96)
	HybriDetect 1 lateral flow strips		MILHY01strip			N/A	4132.56 (96)
	Crystal VC® dipstick	Span Diagnostics Ltd. (Surat, IN)	SKU#16IC101-50			N/A	1894.06 (50)
	Life Assay Test-it™	Life Assay Diagnostics (Cape Town, RSA)	TYP001			N/A	737.42 (25)
	3 drawer storage unit	Macro (Pty.) Ltd. (Johannesburg, RSA)	272619EA			N/A	599.00

A.5. Water compliance monitoring equipment.

Purpose	Equipment	Supplier	Model no.	Dimensions (mm) L x W x H	Weight (kg)	Energy output/usage	Total cost (Rand)
Water compliance monitoring	TDS test meter	Designer water Inc.	N/A	560 x 390 x 610 (size of storage unit)	6	2 x 1.5V (button cell)	5178.34
	Digital pH test meter					4 x 1.5V (button cell)	4808.46
	Portable Turbidimeter	Hach Inc.	2100Q			4 x 1.5V (AA)	23565.30
	H2S test kits					N/A	
	API 20 E test kits	Biomeriux				N/A	
	3 drawer storage unit	Macro (Pty.) Ltd. (Johannesburg, RSA)	272619EA		4	N/A	599.00

A.7. The total power usage and hours used of laboratory equipment.

Equipment	Total power usage	Operational hours/ day
High frequency transceiver	160 W	12
Interior lighting (6 x 12 W)	72 W	12
Exterior lighting (5 x 20 W)	80 W	13
Ventilation fan	15 W	24
Laptop and small battery charger (2 x 90 W)	180 W	12
Reverse osmosis system	54 kW	3*
Water pump	180 W	3*

*the reverse osmosis system will operate on a water need basis so the hours operating per day will vary accordingly, however for simplicity of modeling 3 hours per day was used as reference.

APPENDIX B- Function

B.1. Water compliance monitoring- Hydrogen sulphide

Hydrogen sulphide test kit Methodology

a. Sterilize the outside of the faucet with 70 % ethanol
b. Open faucet for approx. 30 seconds
c. Reduce flow to a continuous trickle
d. Half-fill the test-kit jar containing the dehydrated media with water to the line indicated line.
e. Tighten the lid and shake
f. Place test-kit jar in a sunlight-free area.
g. Observe colour changes in jar 12 hourly for 72 hours.
h. A positive result is indicated by a black precipitate within 72 hours
i. Discard water from jar in a toilet and the test-kit jar in refuse
j. Wash hands with soap anti-bacterial soap thoroughly

B.2. Disease diagnosis– Primer and Probe

The following methodology was optimized for ***Cryptosporidium, Giardia lamblia*** and ***Entamoeba*** by Crannell ***et al***. (2016).

<u>Probe and primer design</u>

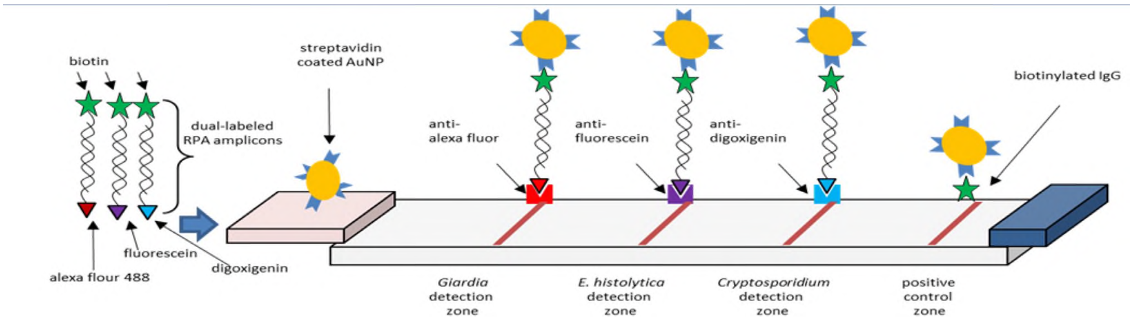
Singleplex RPA reactions were assembled according to the manufacturer's recommended protocol (TwistDx Inc., 2016)

The following modifications were made:

To RPA TwistAmp nfo enzyme pellet 45.5 μL of a master-mix (29.5 μL supplied buffer, 11.2 μL water, 2.1 μL 10 μM forward primer, 2.1 μL 10 μM 5'-biotinylated reverse primer, and 0.6 μL 10 μM 5'-labeled probe) was added. The labels (5') for the ***Giardia, Entamoeba***, and ***Cryptosporidium*** probes were Alexa Fluor®488, fluorescein, and digoxigenin.

Lateral flow detection of multiple targets

The dual-labeled DNA amplicons were detected via lateral flow strips in B.1.



B.1. Visual representation of the lateral flow detection of multiple targets (Crannell *et al.*, 2016).

B.3. Citizen input form

Citizen Input form

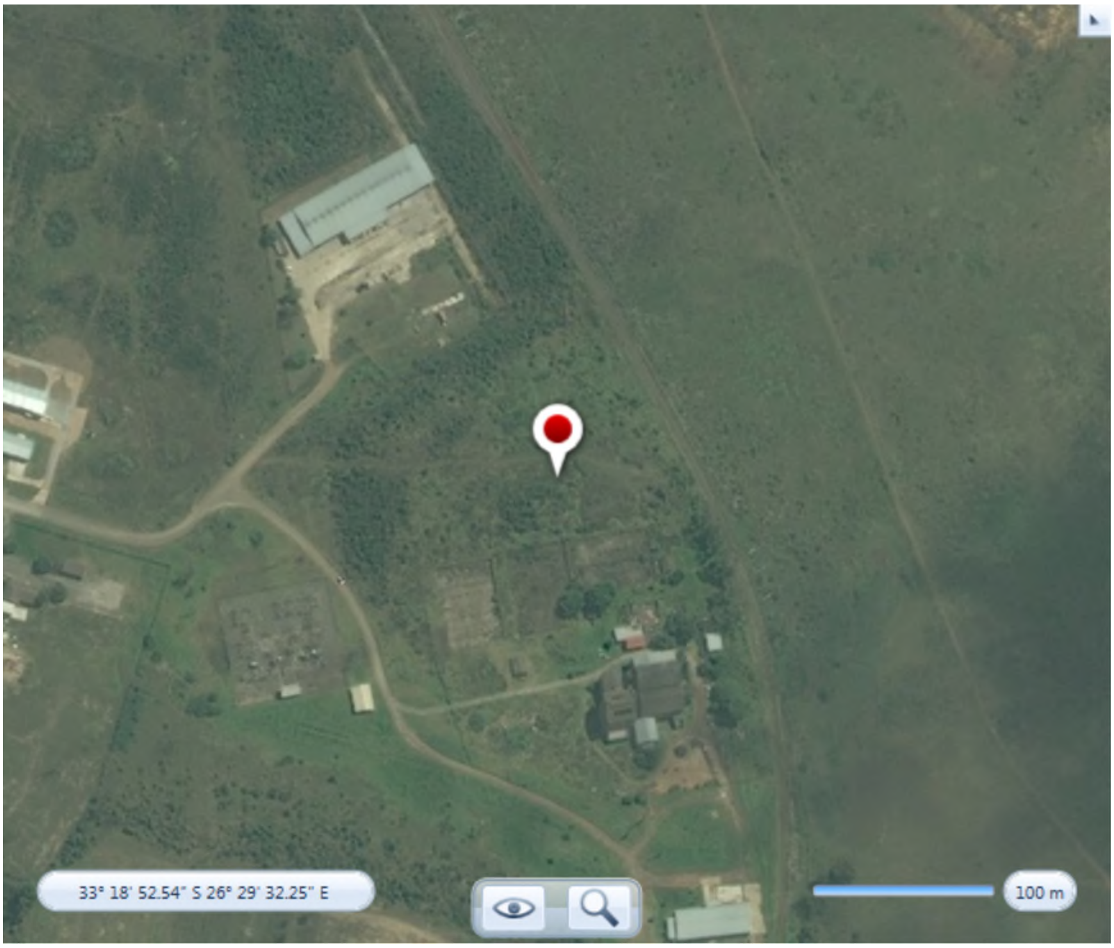
Name:
Gender:
Age:

Please mark the following on the map with a number 1 and 2.
1. Residential Address
2. Water source

For official use only		
Diagnostic results:	Vibrio Cholera	☐
	Salmanella typhi	☐
	Campylobactor jejuni	☐
	Shigella dysentery	☐
	Cryptosporidium parvum.	☐
	parasite Giardia lamblia	
	parasite Entamoeba histolytica.	☐

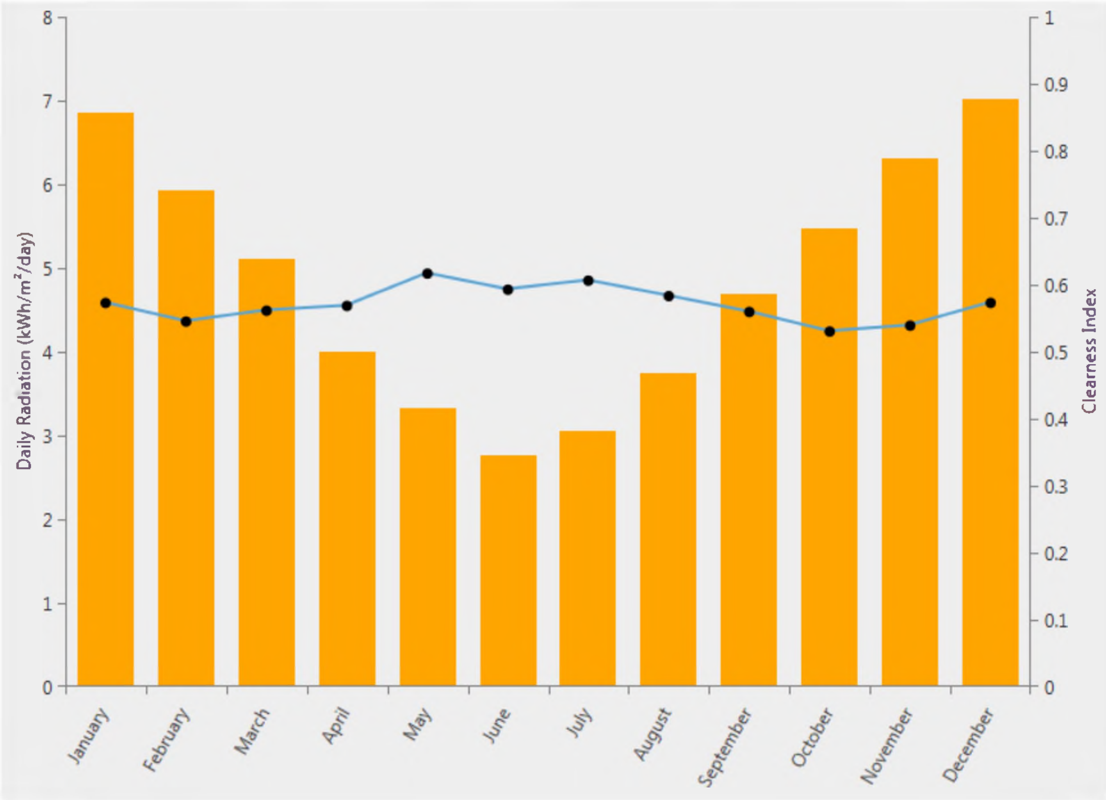
The citizen input form shown will determine the individuals' area of residence and the locations in which he/she has been exposed to water. The figure is an aerial view (Google Earth, 2016) of an example location in Grahamstown East. The information will be logged along with the bacterium or parasite present in that individual; this area will be noted as a priority zone for water compliance monitoring and samples will be tested from the identified water source and based on these results treated water will be supplied.

APPENDIX C- Techno-economic Analysis

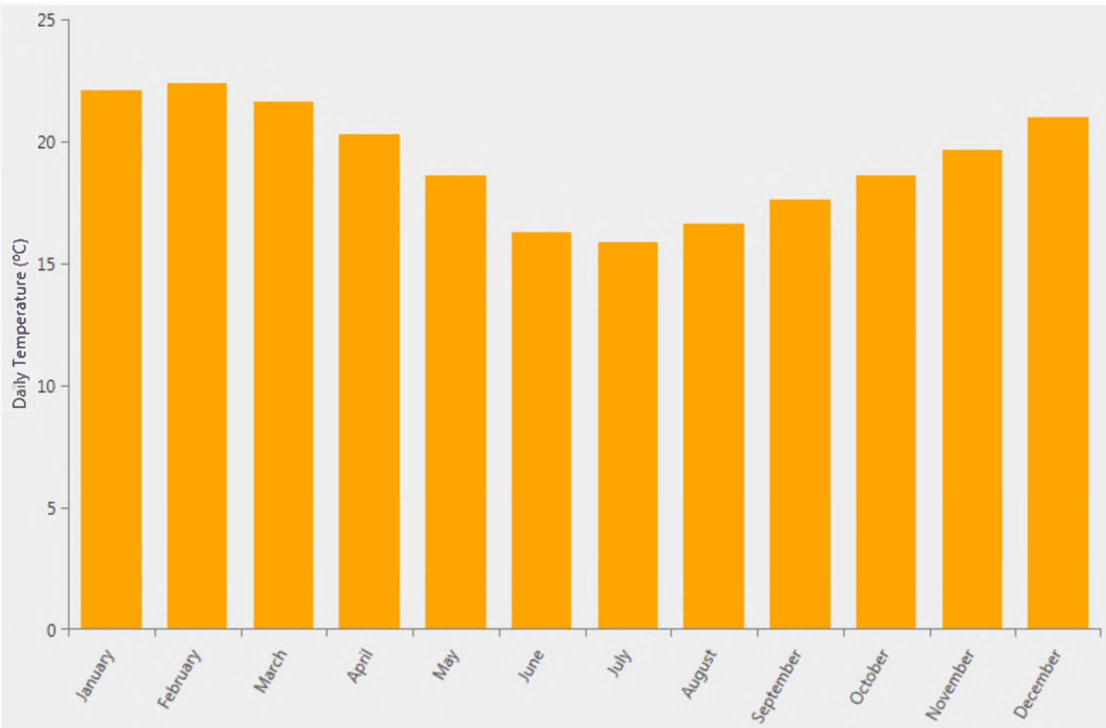


C.1. The aerial view of the site in Grahamstown where the simulation took place (Google Maps, 2016).

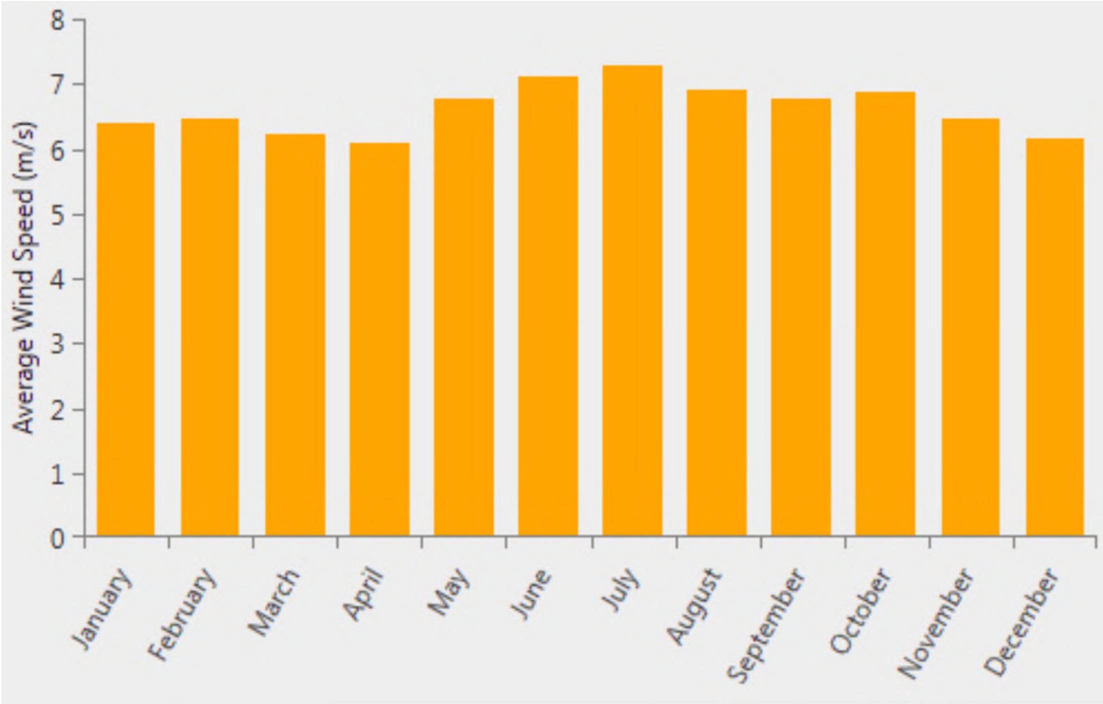
The site selected was in the industrial area of Grahamstown and was selected due to the delocalized setting and off-the-grid placement. All the wind, solar and temperature data was simulated at the site shown in Appendix C.1. The other selection factor was due to the ease of prototyping the mobile laboratory on this site because the land is owned by a Rhodes University stakeholder. The site is a five-minute drive from the centre of Grahamstown, making it easily accessible for researchers.



C.2. The average daily solar radiance and clearness index for Grahamstown for the year 2015 (National Renewable Energy Lab (NREL) database, 2015).

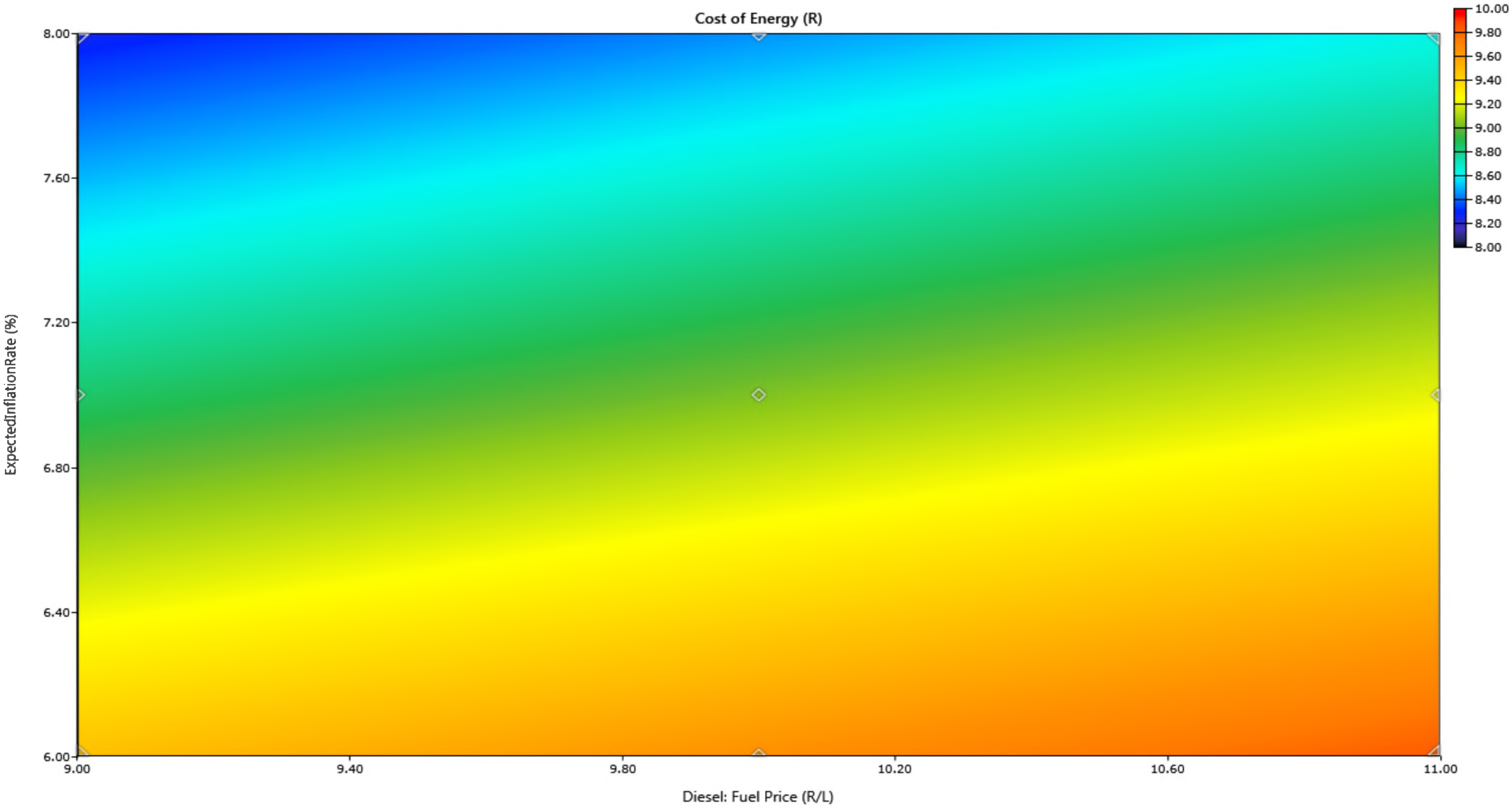


C.3. The average daily temperature for Grahamstown for the year 2015 (National Renewable Energy Lab (NREL) database, 2015).



C.4. The average wind speed for Grahamstown for the year 2015 (National Renewable Energy Lab (NREL) database, 2015).

C.5. The sensitivity analysis of the effect of battery lifetime and project lifetime on the total net present cost (Chap. 4).



C.6. The sensitivity analysis of the effect of inflation and diesel price on the cost of energy (Chap. 4).

APPENDIX D- Human waste processing

D.1. Preparation of simulated human faeces

The simulated human faeces were prepared according to the values shown in Appendix D.1. and the methodology developed by Wignarajah *et al.* (2006).

D.1. Synthetic chemicals used to produce simulated human faeces.

Component	% Weight
Course Sand	30
Cellulose	15
Polyethylene glycol	20
Psyllium	5
Peanut oil	20
Miso	5
Dried course vegetable matter	50 mg
E.coli	3 ml

(Wignarajah *et al.*, 2006)

D.2. The physiochemical properties of leachate from simulated feaces and fly over different time periods.

	Faeces:fly ash (g)	Without inoculum		[1]With inoculum	
		1 Hour	24 Hour	1 Hour	24 Hour
Nitrate (NO_3^+) (mg/L)	1:0	-	-	2.42±0.11	2.85±0.02
	1:1	4.17±0.09	1.66±0.40	2.73±0.18	2.56±0.05
	2:1	6.23±1.15	1.84±0.90	3.78±0.03	2.57±0.09
	5:1	17.63±0.33	9.94±1.03	6.73±0.08	6.51±0.19
	10:1	17.46±4.59	12.44±0.72	13.02±0.19	11.54±0.09
Ammonia (NH_3) (mg/L)	1:0	-	-	2.81±0.01	1.70±0.01
	1:1	1.32±0.15	2.41±0.14	0.35±0.02	1.89±0.02
	2:1	3.96±0.24	4.04±0.33	3.41±0.00	3.56±0.01
	5:1	4.02±0.05	4.03±0.13	3.35±0.02	4.19±0.00
	10:1	3.76±0.13	2.96±0.22	7.72±0.02	7.18±0.01
Phosphate (PO_4^+) (mg/L)	1:0	-	-	8.38±0.07	2.64±0.01
	1:1	2.25±0.17	2.79±0.01	4.85±0.09	2.81±0.01
	2:1	4.28±0.54	4.46±0.67	6.49±0.06	4.59±0.08
	5:1	9.61±2.61	8.87±2.79	13.18±0.03	4.98±0.01
	10:1	10.65±1.06	9.91±1.52	20.30±0.02	14.20±0.01
Chloride (Cl^-) (mg/L)	1:0	-	-	0.12±0.00	0.12±0.00
	1:1	0.12±0.00	0.12±0.00	0.11±0.00	0.11±0.00
	2:1	0.13±0.01	0.14±0.00	0.14±0.00	0.14±0.00
	5:1	0.18±0.02	0.16±0.00	0.19±0.00	0.19±0.00
	10:1	0.17±0.01	0.18±0.01	0.25±0.00	0.24±0.00
Sulfate (SO_4^{2-}) (mg/L)	1:0	-	-	0.16±0.00	0.16±0.00
	1:1	0.16±0.00	0.16±0.00	0.16±0.00	0.16±0.00
	2:1	0.16±0.00	0.16±0.00	0.16±0.00	0.16±0.00
	5:1	0.16±0.00	0.16±0.00	0.16±0.00	0.16±0.00
	10:1	0.16c0.00	0.16±0.00	0.16±0.00	0.16±0.00
[2]COD (mg/L)	1:0	-	-	258±	249±
	1:1	228±	208±	269±	245±
	2:1	259±	204±	289±	224±
	5:1	287±	279±	292±	256±
	10:1	485±	298±	327±	288±

Coliforms ([2]CFU/mL)	1:0	-	-	4,70*10^3	0
	1:1	0	0	7,30*10^3	0
	2:1	0	0	3,35*10^4	0
	5:1	0	0	1,05*10^5	0
	10:1	0	0	0	0
pH	1:0	-	-	6.20±0.00	6.77±0.23
	1:1	6.50±0.00	7.30±0.00	6.30±0.00	7.47±0.06
	2:1	6.10±0.00	7.60±0.00	6.20±0.00	7.40±0.00
	5:1	6.10±0.00	7.47±0.06	5.87±0.06	7.40±0.00
	10:1	6.50±0.00	7.80±0.00	5.53±0.06	6.30±0.00
Turbidity ([2]NTU)	1:0	-	-	65.67±0.58	176.33±0.58
	1:1	112.00±0.00	89.33±0.58	86.33±0.58	98.00±0.00
	2:1	189.00±1.00	116.67±2.08	186.00±2.00	124.67±2.08
	5:1	487.86±4.24	324.67±4.08	404.67±1.16	293.00±4.00
	10:1	923.85±3.85	803.78±5.06	857.33±1.16	774.67±4.62

[1] With inoculum refers to the addition of 3 mL 10th-generation-enterobacter-inoculated Tryptic Soy broth to simulated faeces prior to leaching.

[2] Chemical oxygen demand (COD), Colony forming unit (CFU) and Nephalometric Turbidity Units (NTU)