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COAL-ALTERNATIVE FUEL PRODUCTION VIA THE HYDROTHERMAL CARBONIZATION OF ORGANIC AND WASTE FEEDSTOCK: *ECONOMIC FEASIBILITY AND ENVIRONMENTAL IMPACT IN ZIMBABWE*

A DISSERTATION SUBMITTED TO THE SCHOOL OF ENVIRONMENT AND SOCIETY, TOKYO INSTITUTE OF TECHNOLOGY; IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF ENGINEERING

Andile Blessings Maqhuzu

2020

Dedication

…to my loving wife and son

Abstract

Coal-alternative fuel production via the hydrothermal carbonization of organic and waste feedstock: Economic feasibility and environmental impact in Zimbabwe

by

Andile Blessings Maqhuzu

Doctor of Engineering in Global Engineering for Development, Environment and Society

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Hydrothermal carbonization (HTC) can address the twin issues of pollution and an energy deficit that Zimbabwe is facing. Zimbabwe has a plethora of biomass that can be valorized and utilized in a sustainable manner to produce a coal-alternative fuel via HTC. This can also reduce the impact of coal on the environment.

In chapter 2, we assess the biomass available for conversion to biofuels in Zimbabwe and its energy potential. In this chapter we extended a quantitative methodology involving the use of probability distributions to rigorously address uncertainty in the quantification of this biomass. Prior studies on Zimbabwe's biomass feedstock availability have ignored uncertainty in their analyses because of using deterministic methodologies.

In Chapter 3, we investigate the potential of utilizing MSW in Zimbabwe (ZMSW) as an energy resource for producing electrical power. To do this, the ZMSW is treated using the hydrothermal carbonization (HTC) process to produce a solid fuel, called ZMSWH, which is co-fired with coal in Zimbabwe's existing power plants. Prior to HTC treatment, MSW undergoes a sorting process to remove dirt, glass, metals, and other components that are not amenable to carbonization. The resulting organic fraction of MSW (ZOFMSW) is then properly sized to produce an acceptable feedstock. After HTC treatment, ZMSWH is dried and pelletized before it can be transported to a power

plant. The receiving power has facilities to handle and store the ZMSWH product, and to combine it with coal (in the proper ratio) for combustion. All of these steps add to the emissions of an HTC-based energy system. This is a unique approach, which has the potential to address simultaneously the problems of waste disposal and the need for increased renewable power. To the best of our knowledge, this has not been reported or evaluated at a national scale for any country for HTC.

Although prior research has identified technologies that could be used in MSW treatment, such as incineration and gasification, the implementation could be cost-prohibitive and difficult to administer on a national level in developing countries. In Chapter 4 we assess the economic viability of HTC in Zimbabwe allowing a comparison of the relative costs of HTC and identification of the driving factors that can be improved so that HTC can be employed. The environmental perils of leachate from landfills are well-established. In chapter 5 we modify the water balance model to predict the amount of leachate from Zimbabwe's disposal sites that can be avoided by introducing HTC.

In Chapters 6, we investigate the usage of BSG as another potential feedstock for HTC. The main of objective of this chapter is to compare the global warming potential (GWP) of coal-alternative fuel production using HTC from BSG to alternative uses such as food production. Many researchers have reported on the energy potential, treatment of BSG and nutritional aspects of BSG. Very few researchers, however, have given a detailed country level analysis on BSG generation rates, global warming potential of BSG usage for either energy or food. To the best of our knowledge no research has been conducted to forecast BSG generation rates despite the immense potential of this agro-industrial waste as both a source of food and energy. BSG contains protein (19-30% w/w) with clear uses for feed and potential uses for food. We explore the availability and energy potential of biochar derived from BSG using HTC and further compare it to the amount of flour that can derived from BSG as an alternative to BSG usage. The GWP of alternative BSG treatment options are compared, namely landfilling and animal feed. Such information, to the best of our knowledge has never been reported in detail.

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If I have seen further than others, it is by standing on the shoulders of giants. - Isaac Newton

Originality statement

This is to certify that to the best of my knowledge; the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes. I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Andile Blessings Maqhuzu

Table of Contents

Contents

List of Figures

List of Tables

List of Abbreviations

AIC: Akaike's Information Criterion
BOT: Build–operate–transfer
BSG: Brewer's spent grains
BSGF: Brewer's spent grain flour
BSGH: Brewer's spent grain hydrochar
CAGR: Compound annual growth rate
ET: Evapotranspiration
GDP: Gross domestic product
IRR: Internal rate of return
PDF Probability Density Function
HTC: Hydrothermal carbonization
GWP: Global warming potential
MRU: Maintenance and Repair Unit
MSW: Municipal solid waste
NPV: Net present value
PI: Profitability index
PERT: Program (or project) evaluation and review technique
PPP: Private-public partnerships
ROI: Return on investment
SSA: Sub-Saharan Africa
TCI: Total capital investment
TCPL: Total Consumption Poverty Line
TOC: Total Organic Content
WTE: Waste-to-energy
WBM: Water Balance Method
ZIMRA: Zimbabwe Revenue Authority
ZMSW: Zimbabwe municipal solid waste
ZMSWH: Zimbabwe hydrochar/coal-alternative fuel
ZOFMSW: Zimbabwe organic Fraction of Municipal Solid Waste

List of Publications

1. Maqhuzu AB, Yoshikawa K, Takahashi F. The effect of coal alternative fuel from municipal solid wastes employing hydrothermal carbonization on atmospheric pollutant emissions in Zimbabwe. Science of The Total Environment 2019; 668: 743-759.
   https://doi.org/10.1016/j.scitotenv.2019.03.050

2. Maqhuzu AB, Yoshikawa K, Takahashi F. Stochastic economic analysis of coal-alternative fuel production from municipal solid wastes employing hydrothermal carbonization in Zimbabwe. Science of The Total Environment 2020; 716: 135337.
   https://doi.org/10.1016/j.scitotenv.2019.135337

3. Maqhuzu AB, Yoshikawa K, Takahashi F. Estimation of Leachate Generated from Zimbabwe's Municipal Solid Wastes (MSW) Landfills using a Simple Stochastic Water Balance Model. Applied Environmental Research 2018, 40(2), 40-50. https://doi.org/10.35762/AER.2018.40.2.4

4. Maqhuzu AB, Yoshikawa K, Takahashi F. Prospective utilization of brewers' spent grains (BSG) for energy and food in Africa and its global warming potential. Sustainable Production and Consumption 2021; 26: 146-159. https://doi.org/10.1016/j.spc.2020.09.022

List of International Conferences

1. Maqhuzu AB, Yoshikawa K, Takahashi F. Potential for thermal conversion of brewer's spent grain into biocoal via hydrothermal carbonization in Africa. Energy Procedia 2019; 158: 291-296. 10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

2. Maqhuzu AB, Yoshikawa K, Takahashi F. Biofuels from agricultural biomass in Zimbabwe: Feedstock availability and energy potential. Energy Procedia 2017; 142: 111-116. 9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

3. Maqhuzu AB, Yoshikawa K, Takahashi F. Estimation of leachate generated from Zimbabwe's MSW-landfills using a simple stochastic water balance model, Proceedings of 4th EnvironmentAsia International Conference on Practical Global Policy and Environmental Dynamics "EnvironmentAsia 2017", 65-72, Bangkok, Thailand, 21-23rd Jun.

4. Maqhuzu AB, Yoshikawa K, Takahashi F. A Monte Carlo analysis of the economics of hydrothermal conversion of municipal solid wastes to a coal-alternative fuel in Zimbabwe, Proceedings of 3rd Symposium of the Asian Regional Branch of International Waste Working Group "iwwg-ARB2017", 112-114, Seoul, South Korea, 12-14th April.

Chapter 1: Introduction

In this chapter, an overview of Zimbabwe's need for a waste management strategy and improved bioenergy sector is highlighted. The gap in hydrothermal carbonization research and waste-to-energy research in Zimbabwe is highlighted. The problem statement and motivation are also given. Finally, the research questions and chapter relation are addressed.

1.0 Current situation in Zimbabwe

Zimbabwe is a non-coastal, low-income republic situated in southern Africa with an estimated population of 15.6 million in 2015. Zimbabwe's economy is anchored by mining, tourism and agriculture and the Gross Domestic Product (GDP) per capita in 2017 was pegged at US$1,333.39 [1]. Zimbabwe is confronted by a severe energy crisis characterized by insistent load shedding and power blackouts which undermine the development of the economy and people's livelihood. An estimate of the cost of electricity supply outages in Zimbabwe in 2009, was about US$1.8 billion [2]. Energy shortages are prevalent in much of Sub-Saharan Africa (SSA), which still suffers from a serious electricity lag with roughly 633 million people living without access [3]. Roughly 80% of those deprived of electricity live in rural areas [4]. Reliance on wood-based biomass energy (fuel wood and charcoal) for cooking is higher in SSA, at 792 million people, than any other region [3, 5]. According to [6] approximately 8.7 million Zimbabweans have no access to electricity.

Deforestation and woodland degradation are problems of great concern in Zimbabwe which inevitably result from the demand for fuelwood amongst other factors [7]. The use of traditional biomass along with its unsustainable harvesting and inefficient use is a gross mismanagement of natural resources. Despite the resounding reliance on bioenergy in Zimbabwe, the planning, management, production, distribution and use of biomass, hardly receives commensurate attention at national policy agendas. A possible approach to energy sustainability, is the modernization of the bioenergy sector. The rationale for engagement and development in this sector are threefold; mitigation of climate change and greenhouse gas (GHG) emissions, poverty alleviation and economic development and energy security improvement.

Waste management still remains a key social and engineering concern due to the health hazards associated with poor waste treatment. Although municipal solid waste (MSW) disposal is shifting from mere landfilling to more integrated and sustainable systems such as waste-to-energy (WTE) in developed nations, the instigation of such viable waste management practices in developing nations such as Zimbabwe is still confronted by a lack of political willpower, weak financial capacity and a lack of technical expertise. Zimbabwean municipalities, in particular, are incapacitated as most urban areas are teeming with uncollected waste, adversely affecting the aesthetics and more importantly, making the inhabitants more susceptible to health risks. Local authorities are confronted by unprecedented levels of MSW generation compounded by financial constraints which are dampening their efforts in curbing the rising problem [8-10]. This has taken a toll on the existing waste management and sanitation systems as demonstrated by the unusually high fatality rates in urban areas during a 2008 cholera epidemic [11, 12]. With a waste management crisis on the one hand and an energy deficit on the other, appropriate waste management based on social, economic, and environmental considerations is essential for the environment-friendly development of Zimbabwe.

1.1 Coal-alternative fuel from the hydrothermal carbonization of organic and waste feedstock

The development of low energy intensive technologies that can utilize organic feedstock to produce green products with a potential high added value is essential for the sustainable management of organic and waste materials in Zimbabwe. HTC involves the conversion of carbon feedstock in subcritical water under moderate temperature between 200–300 °C and autogenous pressure in the range of 2–10 MPa [13] to yield a coal-like biochar. HTC residence time varies and reaction rates are largely unknown but typically times between 1 and 72 hours have been quoted in literature. Increasing reaction severity by either raising the temperature and/or increasing residence time gives a hydrochar with higher carbon content but lower yield [14]. Scholars agree that the mechanism is governed by several chains of chemical reactions including hydrolysis, dehydration, decarboxylation, polymerization and coalification [15]. Biomass is submerged in water at varying water to biomass loading ratios generally from 0.3 to 10 [16]. Most recently a weight ratio of 12:1 for woody biomass was used by [17] and 3:1 for banana peels [18]. HTC is preferentially suitable for high raw material water content [19]. A high moisture content in the feedstock makes the other alternative technologies, gasification and pyrolysis, uneconomical [20].

HTC is preferentially suitable for high raw material water content [19]. It is hailed for its lower energy requirement [13], high hydrophobicity and grindability of its hydrochar [21], high hydrochar yield with a high carbon content [22]. The versatile hydrothermal treatment of biomass in subcritical water has attracted considerable interest over the years and substantial testing on a laboratory and pilot scale on organic fraction of MSW (OFMSW) upgrading has been reported [23-25]. Companies promoting HTC today include C-Green, SunCoal, AVA GmbH and Ingelia S.L applying the technology to various feedstocks [26]. Positive results obtained during demonstration campaigns have spurred the replication of the process in other countries across North America and Europe. HTC is now at various levels of development. The first industrial-size HTC plant (annual capacity of 8,400 tons of biomass) was commissioned in Karlsruhe, Germany in October 2010 spearheaded by the Swiss company, AVA-CO2 [20, 27]. A commercial plant has been setup in Indonesia to handle OFMSW based on the HTC process developed at Tokyo Institute of Technology [28, 29]. Biomass resources in Zimbabwe include agricultural waste, MSW, forestry residues, animal waste and industrial wastes that can play an important role in the development of sustainable energy systems in Zimbabwe.

1.2 Overview of research on organic and waste feedstocks in Zimbabwe

Researchers have reported on the quantity and characteristics of Zimbabwe's MSW. A substantial number of reports on Zimbabwe's MSW composition and characteristics are available [9, 30-41]. Important findings from these studies are the high content of paper (18.8 ± 3.2%) and plastics (16.1 ± 3.5%) found in Zimbabwe's MSW stream and relatively low organic fraction (32.9 ± 6.6%) which favours HTC as these components contribute to the calorific value. They also found the coverage of MSW receptacles to be low at about 50% in all urban areas. These reports concur on the high level of dissatisfaction expressed by residents with the current MSW collection and disposal system. Other reports have estimated the availability and energy potential of biomass sources such as fuelwood, charcoal, animal waste, crop residues, sawmill waste and forestry waste. Other researchers have focused on the environmental impact of Zimbabwe's waste [42, 43] and possible solutions alluded to by [44-49]. Estimations on the energy potential of Zimbabwe's MSW have been given by [50-52] who have gone on further to suggest its exploitation via biogas technologies (either anaerobic digestion or landfill gas recovery). [53] suggested incineration while [54] focused on biochar production via pyrolysis. These papers highlight that MSW management strategies exhibit antagonistic tendencies due to the involvement of various government ministries, departments and non-governmental organizations and incoherence among them which weakens the overall strategy.

Awareness on legislation and policies is lacking amongst stakeholders. Local authorities' tariff charges cannot sustainably meet the cost-of-service delivery. Biomass energy resources in Zimbabwe and their energy potential have been reported by [51, 55]. However, these estimations were deterministic and did not account for uncertainty. None of the studies, however, have considered the impact of their suggested technologies on the environment at a national level.

As there are limited industrial scale HTC systems in operation, there exists a considerable gap in the economic evaluation of HTC systems [56]. While the economic viability of the conversion of OFMSW is yet to be demonstrated, recent analyses only revealed the profitability of converting separated food waste [57, 58]. Techno-economic models focused on yard waste [59]. Other researchers assessed the co-HTC of a miscanthus-coal blend [60]. In other reports, biogas digestate [61], wood chips [62], palm oil empty fruit bunches [63, 64] and wheat straw [65] were assessed as feed. Although HTC can be applied to a plurality of biomass resources; the optimal choice of feedstock should also ensure investors can sustain their margins. The spatial and temporal availability of biomass (due to seasonality) greatly impacts collection, transport and storage costs [66]. Agro-industrial wastes, forestry biomass or agricultural residues, for example, can generate large amounts of hydrochar during the harvesting and processing season, however, during the off-season the HTC plant could potentially remain idle. Currently no study has conducted an environmental and economic analysis on a proposed technology as a means of holistically evaluating waste to energy technology in Zimbabwe.

1.3 Problem Statement and Motivation

Hydrothermal carbonization has become an increasingly important contender in the waste-to-energy sector. Pyrolysis, incineration and gasification are the conventionally accepted methods for handling organic and waste feedstock. Extensive research at a laboratory level has been conducted and HTC's viability has been demonstrated. Still, research is undergoing to determine its feasibility in a number of process configurations and its application to various feedstocks is being investigated. The technology has transitioned into pilot and full-scale stages in certain areas, but there has been little work exploring the environmental impact and economic feasibility of this technology at a national level. Zimbabwe is endowed with various biomass feedstocks; however, the quantification is mostly uncertain. Most estimations of Zimbabwe's feedstocks are deterministic, but the uncertainty of these resources must be estimated when they are utilized for decision support. Therefore, the quantification of these feedstocks for HTC using stochastic models and the impact of HTC on the environment and the feasibility of the process at a national scale were assessed in this study.

1.4 Overall objective of the study

The overall objective is to improve the availability of assessment information to assist in implementing a nationwide organic and/or waste to energy system based on hydrothermal carbonization in Zimbabwe

1.5 Origin of critical data

Due to the nature of the study involving several calculations or estimations, it is worth noting were the critical data originated from. This is shown in Table 1.1.

Table 1.1 Origin of critical data

Chapter 2: Availability & energy potential of organic & waste feedstocks	
Parameters cited for Zimbabwe	**Parameters from other countries (country name)**
• Number of Livestock • Annual Crop Production • Wood production	• Dung Accessibility and Collection Factor (Kenya, USA, India) • Dung output for animal (Kenya, USA, India) • Residue-product-ratios (UK, Kenya, Zambia) • Residue energy value (Kenya, Zambia)
Chapter 3 - Effect of coal-alternative fuel production from MSW via HTC on atmospheric pollutant emissions	
Parameters cited for Zimbabwe	**Parameters from other countries**
• MSW Generation Rate • MSW Collection Efficiency • MSW Composition • Population size and Urban Density • Fugitive Methane Emission Factor for underground coal mining • Zimbabwe steam coal properties • Haulage Distances • Capacity of thermal power plant	• MSW Proximate and Ultimate Analysis (U.S.A, India, China) • Typical Moisture Content and Heating value of MSW (U.S.A) • Nitrogen Emission Factor for coal combustion (U.S.A) • GWP values of CO_2 and CH_4 (Paris) • Carbon dioxide emission factors for diesel fuels (U.S.A) • Methane emission factors for non-highway mobile combustion (U.S.A) • Emission factors for diesel locomotives (Australia) • Emission factors for diesel heavy truck (International) • Fuel economy of diesel train (U.S.A) • Fuel economy of refuse truck (U.S.A) • HTC Yields (China, U.S.A) • MSW Sorting equipment Efficiencies (U.S.A)
Chapter 4: Stochastic economic analysis of coal-alternative fuel production from MSW	
Parameters cited for Zimbabwe	**Parameters from other countries**
• Tax rate, Import Duty • Tariff/MSW Collection fee • MSW Collection Fleet requirements	• Equipment Costs (China) • MSW fleet Costs (China, South Africa) • Fuel Economy of refuse and haulage trucks (U.S.A)

• Process water cost per unit volume • Waste water treatment costs • Electricity tariff • Diesel Pump Price • Labor Costs	• Engine Oil Consumption (U.S.A) • Maintenance costs (spares, tires, etc.) (U.S.A)
Chapter 5: Estimation of avoided leachate produced from uncontrolled landfill disposal sites	
Parameters cited for Zimbabwe	**Parameters from other countries**
• Historical rainfall data (weather bureau data) • Temperature data • Daylight hours • MSW Chemical Formula (Calculated)	• Runoff coefficients (USA) • Constants (USA)
Chapter 6: Comparative global warming potential assessment of BSG for coal-alternative fuel production and food	
Parameters cited for Zimbabwe	**Parameters from other countries**
• Annual Beer Production	• Carbon footprint of potable water (South Africa) • Life-cycle GHG emissions for coal-fired electricity (South Africa) • CO_2 -emission factor for average freight truck (Europe) • CO_2 -emission from rail transport operations (USA) • Specific power consumption of equipment (USA) • BSG maximum biogas potential (Europe) • Yield of biochar from hydrothermally converted BSG (USA) • Yield of BSGF from milled BSG (USA)

1.5 Thesis Structure

Chapter 2: To determine the availability and energy potential of other organic feedstocks for HTC and its global warming potential

Chapter 3: To determine the environmental impact of MSW derived coal-alternative fuel production using HTC

Chapter 4: To determine the economic feasibility of MSW derived coal-alternative fuel production using HTC

Chapter 5: To determine the quantity of leachate that can be avoided in landfills by introducing HTC

Chapter 6: To determine the environmental impact BSG derived coal-alternative fuel using HTC

1.6 Research questions

Chapter 2

1. What is the quantity of available organic/biomass and waste feedstocks?
2. What is the energy potential of these feedstocks?

Chapter 3

1. What are the characteristics of Zimbabwe's MSW?
2. What yield of coal-alternative fuel can be expected from Zimbabwe's MSW?

3. What is the impact of an HTC -based waste management system on the atmosphere?

Chapter 4

1. To what extent is an HTC- based waste management system economically feasible in Zimbabwe?
2. What conditions can make the proposed system more viable?

Chapter 5

1. What is the current leachate generation rate from disposal sites?
2. How much leachate generation can be avoided after introducing HTC?

Chapter 6

1. What yield of BSG-derived coal-alternative fuel can be expected?
2. What is the global warming potential of a BSG-HTC system?
3. How does the above system compare with alternative uses or disposal methods?

1.7 Chapter relation

The overall relationship between all the chapters of this study, summary of the research objectives and outcomes are summarized in **Fig. 1.1**.

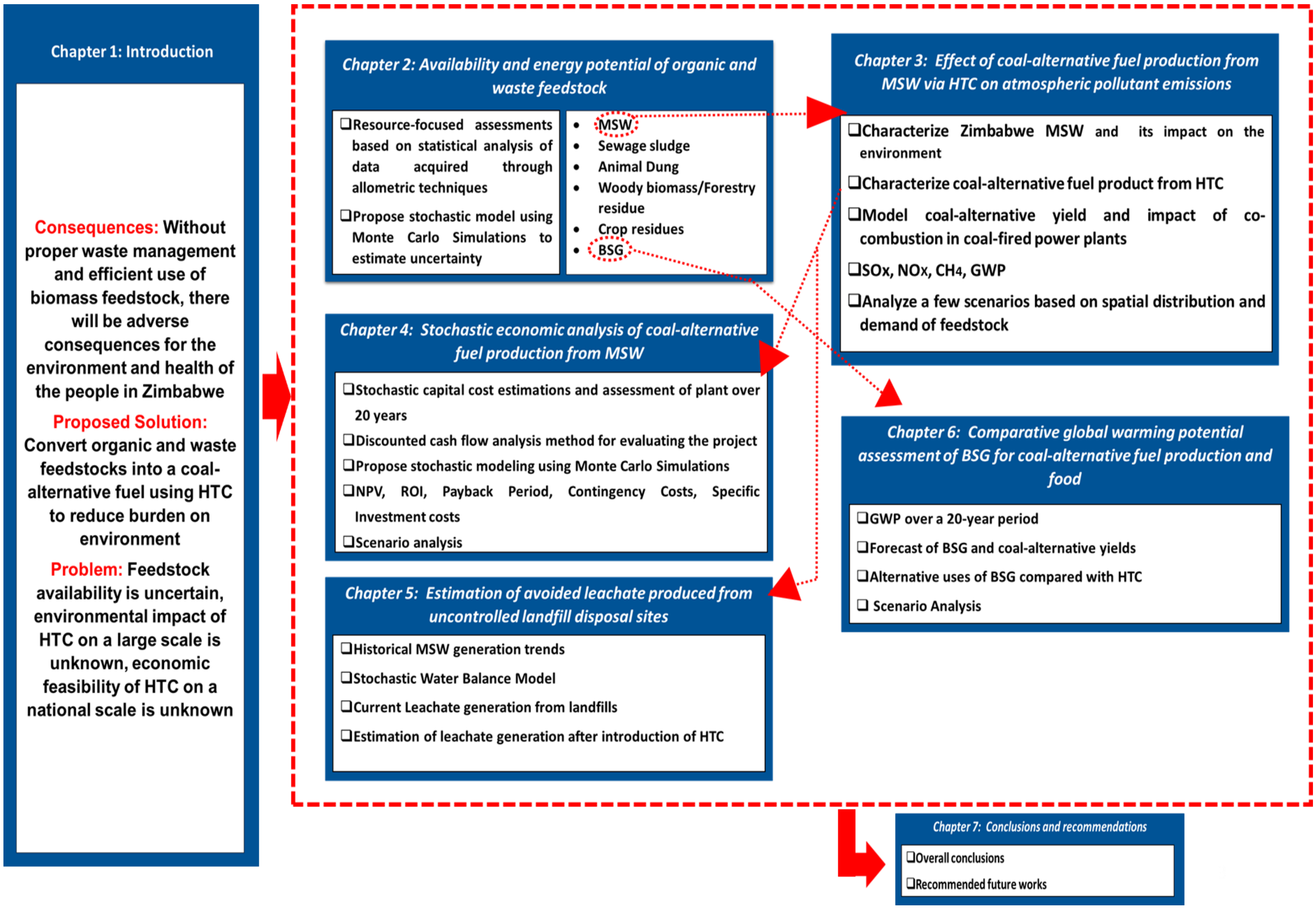


Fig. 1.1 Summary of Chapter relation

1.7 Originality of the research

As summarized in **Fig 1.2** below, the present work introduces the application of HTC in Zimbabwe as it has previously not been studied within the context of Africa. Prior research work on HTC has concentrated on laboratory analysis and this research differentiates itself by embarking on a study that covers its applicability on a larger scale. Previous research on the feedstocks available in Zimbabwe has been deterministic without any quantification of the uncertainty in the estimates given. The present work covers a greater scope in detailing the previous works especially in Zimbabwe and hence gives a broader view of the Zimbabwean situation and HTC. A more holistic approach was adopted with the investigation of the applicability of HTC as both environmental and economic perspectives were considered unlike previous researchers who only focused on one aspect for their proposed technologies.

Fig. 1.2 Originality of the research

Chapter 2: Availability and energy potential of organic and waste feedstocks

Here in this chapter, the feedstocks available in Zimbabwe for conversion to biofuels are quantified and results compared to previous research results. Their energy potential is also presented. As a basis for subsequent chapters, the waste feedstocks of particular interest (namely MSW and BSG) are highlighted and after explaining their peculiarity, are further analyzed in following chapters.

2.0 Introduction

The exploitation of biomass is a much-needed lifeline to cope with prevalent issues of inadequate energy supply, energy diversification and sustainability in Zimbabwe. The promotion of sustainable bioenergy production from agricultural wastes and crop residues requires, as an initial step, the quantification of the potentially suitable feedstocks and subsequent residue generation rates. A model that can accurately predict the probable availability of biomass for biofuels is therefore needed to make well- grounded decisions. The uncertainties associated with agricultural and livestock productivity imply that the quantity of biomass (dung and crop residues for example) available for conversion into biofuels is a function of random events. Agricultural output in Zimbabwe, for example, has been declining over the years resulting in persistent cereal shortfalls. Deteriorating soil fertility, erratic rainfall patterns, high input costs, low management standards and instability in the market have contributed adversely to the sustainability of the farming sector [67]. The practice of spreading crop residues such as stover, dry grass or leaves commonly referred to as mulching is not prevalent in communal farms in Zimbabwe. A certain quantity of residue must be used as field cover depending on soil properties, field slope, crop rotation, and tillage system amongst other factors to reduce soil erosion and recycle nutrients. Instead, crop residues are either burned after harvesting or used as stock feed [68] directly competing with the residues available for bioenergy production. Livestock productivity faces similar risks arising from the natural environment, maladapted livestock and the socioeconomic context [69].

Another underutilized source of biomass that could be exploited for energy production in Zimbabwe is residual woody biomass from the timber industry. This industry is a key contributor to Zimbabwe’s Gross Domestic Product (GDP) but despite being an earner, the industry is characterized by obsolete technologies, low levels of efficiency and recovery leading to massive waste generation rates. Reportedly as little as 40-45% of roundwood is recovered from the harvested and processed wood. In addition, an undetermined quantity of infield waste is left in the plantations during harvesting and it is not uncommon for it to be burnt inefficiently on site [70, 71]. Roughly 15-40% or more of the above-ground volume of felled trees may be left on site as branches and crooked stem wood are considered as undesirables [71]. This exerts stress on the environment, moreover, the heaps of waste are a major eyesore and cause for concern as some of the waste is contaminating water supplies. Firewood accounts for over 50% of Zimbabwe's primary energy needs. Only 32.3% of the population is connected to the national grid [72] with some inconsistencies in the supply of electricity which have incited alarming deforestation rates as both urban dwellers and the rural populace scramble for wood. It is estimated in the 15-year period, from 1990 to 2005, Zimbabwe lost 21.1% of its forest cover, or around 4,694,000 hectares amounting to an average annual deforestation rate of 1.41% [73]. In order to avert the impeding desertification of Zimbabwe, the conversion of residual woody biomass to bioenergy could alleviate the pressure on forests and woodlands. However, the quantification of this residual woody biomass is inherently difficult because of several reasons; unreliable or insufficient data, disagreements in the standard units of mensuration, informal use of wood is not accounted for in statistics, biomass yields are largely dependent on unpredictable or variable factors such as biomass species, agro-climatic region, rainfall patterns and management techniques employed in biomass production [71]. Recently, the performance of Zimbabwe's timber industry has been subdued due to socio-economic and political factors thus creating more uncertainty about the future. Despite these misgivings, the determination of the quantity of wood waste generated is necessary to assess the viability of investing in bioenergy conversion technologies. Zimbabwe's timber industry is characterized by low conversion efficiencies resulting in high waste generation rates. Growing stockpiles of sawdust, shavings and offcuts can be found lying idle in eastern Zimbabwe despite wood being a renewable and more sustainable energy source. The diversion of some of this residue to thermochemical processes for bioenergy production can prove to be more useful given the prevailing situation of power shortages in Zimbabwe.

2.1 Overview of biomass estimation methods

Driven by the need to quantify biomass resources at a country level when quality and availability of data are limited, a wide range of estimation strategies have emerged. Batidzirai et al [74] identified 5 approaches (overall guiding philosophies) used in bioenergy resource potential assessments. These include resource-focused, demand-driven, integrated, impact and feasibility assessments and review (or synthesis) approach.

Resource-focused assessments estimate the total bioenergy resource base and the competition between different uses of the resources (supply-side). Some notable works include those by [75, 76]. Demand-driven assessments analyze either the competitiveness of bioelectricity and biofuels or estimate the quantity of biomass required to meet targets on climate-neutral energy supply (demand side) [77]. Highly cited papers by [78, 79] used this approach. Integrated assessments merge demand-driven and resource-focused approaches commonly through the development of integrated assessment models (IAMs) intended to answer policy questions by means of scenario analysis. Authors such as [80, 81] used integrated techniques. Impact and feasibility assessments consider the economic feasibility [82-84] or environmental impact of bioenergy production [85, 86] costs and energy consumption of bioenergy chains [87]) or the impact of bioenergy policies on certain aspects, such as water supply [88], land [83, 89, 90], food security [91], biodiversity, [92], climate change [93] and employment [94-96]. Review approaches [97-99] base fresh insights on previous works. Within each approach are several methodologies ranging from simple statistical methods to more multifaceted spatially explicit models and integrated assessment modelling frameworks.

Among the different approaches, resource-focused assessments stand out as the most popular [74] hence the choice in this paper. Broadly speaking, methodologies in resource-focused assessments can be divided into two [100]: (i) statistical analysis of data acquired through sampling and allometric techniques and (ii) spatially explicit analysis (integrated remote sensing (RS) and geographic information system (GIS) techniques). Limited only by its exclusion of macro-economic and social impacts, a statistical analysis is relatively simple, more transparent, easily reproducible and less demanding in terms of cost. Although transparent in its methodology, a spatially explicit analysis suffers from a lack of reproducibility because GIS software and spatially explicit data can be labor-intensive [74]. The increased complexity of the combined data often confers a degree of uncertainty and contradictions [101]. The many variations in the quantification of bioenergy potentials are due to the complexities in biomass production and use. There are challenges in estimating biomass resource availability due to lack of reliable data or inaccurate data where available. The competing uses of biomass bring further complications and given the myriad conversion technologies, as well as varying socio-economic contexts there is considerable uncertainty in energy potentials. The methodology adopted in this study is a resource-focused approach with statistical analysis. This study aims to deal with the uncertainty in the availability of biofuel raw materials by introducing probabilistic models supported by Monte Carlo simulations to predict organic and waste feedstock generation rates.

2.2 Materials and Method

2.2.1 Crop residues and animal dung estimations

The proposed model was developed on an Excel spreadsheet equipped with Palisade's @Risk risk-profiling plug-in software tool. First biomass production data was retrieved from FAOSTAT's normalized database for crop and livestock production. Data for the major agricultural crops and livestock for the country of interest was then extracted. The annual production data (1961-2014) for each category was fitted to a suitable distribution based on Akaike's Information Criterion (AIC). Distribution fitting allows the development of valid models of random events thus minimizing errors due to selection of unrepresentative probability models. For example, an assumption of a normal distribution for crop outputs would introduce error if real-life data suggests an alternative model. The penultimate step of estimating the quantities of the potential and actual available biomass for biofuel production and its energy content was carried out using equations (1) to (4). The potential amount of crop residues generated was calculated using the formula:

$$P_{CR} = C_{iPDF} \times Y_{RPR} \tag{1}$$

P_{CR} is the potential amount of crop residue available for bioenergy production in Mg/yr assuming non-competitive/alternative uses, C_{iPDF} is the annual crop production in Mg/yr based on the probability distribution function for crop i and Y_{RPR} is percentage yield of residue based on reported residue-product-ratios [102, 103]. From (1), the actual available crop residue (A_{CR}) for bioenergy production after accounting for collection efficiency and competitive uses of residues can be estimated by

$$A_{CR} = P_{CR} \times (1 - p) \quad (2)$$

p is the percentage of P_{CR} collected, and diverted to other uses based on a probability distribution function. A uniform distribution function was assumed for *p* with maximum and minimum values of 80% and 10% respectively. Similarly, for the potential (P_D) and actual amount of dung (A_D) available the formulas used are shown below:

$$P_D = L_{iPDF} \times D_{iR} \quad (3)$$

$$A_D = P_D \times D_{ACF} \quad (4)$$

L_{iPDF} is the number of livestock based on the probability distribution function for animal *i*, D_{iR} is the Dung output for animal *i* (Mg/yr) and D_{ACF} is the Dung Accessibility and Collection Factor which was assumed to lie between 0 and 0.8 in this study. The potential and actual exploitable heat content were estimated by multiplying these equations with specific heating values, assuming a uniform distribution between lowest and highest reported figures when necessary. For example, dung specific heating value is cited to be 9.8 GJ/Mg by [104] and 11.4 GJ/Mg by [55] hence a uniform distribution, U(9.8,11.4) would be more representative of dung heating value. Finally, Monte Carlo simulations were performed to evaluate the risk of results.

2.2.2 Residual woody biomass estimation

A stochastic forestry mass balance (Fig. 2) was developed on a spreadsheet equipped with Palisade's @RISK risk analysis software to ascertain the available woody biomass and forestry waste. Input values for the quantities of forestry products (black colored blocks) were given by probability distribution models. These models were developed by selecting the best fitting model for the historical production data (1961-2015) provided by FAO using @RISK's distribution fitting feature that can use Akaike Information Criterion to select the best model. FAO data reported in cubic meters was converted to oven or bone-dry mass by multiplying the volume by a probability model fitted to the global wood density database (oven dry mass/fresh volume) compiled by [105]. Growing wood stock was estimated using a probability distribution; multiplying the land area of Zimbabwe (39.08 million ha) by a triangular distribution defined by a minimum, a most likely value, and a maximum for the wood stock density.

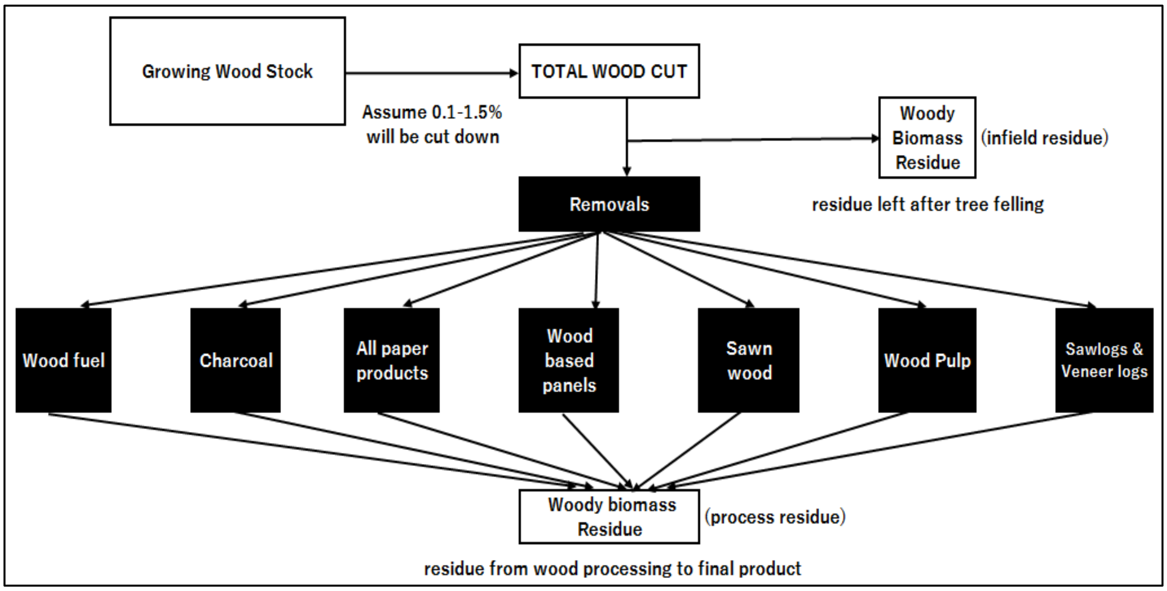


Fig. 2.1 Forestry sector mass balance

The average (most likely) growing stock density across Zimbabwe is 30.2 t/ha (ranging from 6.1 to 37.3 t/ha) [106]. Total Wood cut was estimated using a uniform distribution with minimum and maximum value of 0.1 and 2% respectively. One hundred thousand Monte Carlo simulations were then performed using @RISK to determine the residual woody biomass. From Fig.1; total wood cut minus removals and removals minus products give the residual woody biomass after tree felling and wood processing respectively.

2.2.3 Sewage sludge estimation

Sludge production was estimated in two ways on an Excel spreadsheet equipped with Palisade's @RISK risk analysis software as described below:

Method 1 : Sewage sludge production per capita values reported by [107] were fitted into a probability distribution model using @RISK. The best model was selected based on

Akaike's Information Criterion (AIC). The sludge generation rate was then derived from the product of this distribution and the urban population of Zimbabwe.

Method 2: The wastewater flowrate was first estimated based on World Bank Data. Equations (5 and 6) reported by [108], together with the typical coefficients and empirical data were used to estimate sludge production (dry solids per day) assuming a complete mix suspended growth biological sewage wastewater process. Uniform distributions were used for all data ranges given by [108]. The net waste activated sludge produced per day is given by summation of the following equations:

$$P_{X,VSS} = 0.001\left[\frac{QY(S_0-S)}{1+(k_d)SRT} + \frac{f_d k_d QY(S_0-S)SRT}{1+(k_d)SRT} + \frac{QY_n NO_\lambda}{1+(k_{dn})SRT} + Q(nbVSS)\right] \quad (5)$$

$$P_{X,TSS} = \frac{A}{0.85} + \frac{B}{0.85} + \frac{C}{0.85} + D + Q(TSS_0 - VSS_0) \quad (6)$$

where A, B,C D represent consecutive terms in (1), Q is the influent flowrate (m^3/d), Y is the biomass yield (g VSS/g COD used), S_0 =influent soluble substrate concentration (bsCOD) (g bsCOD/m^3), S =effluent soluble substrate concentration (bsCOD) (g bsCOD/m^3), k_d =endogenous decay coefficient (g VSS/g VSS·d), SRT = Sedimentation Retention Time (d), f_d =fraction of biomass that remains as cell debris (g VSS/g VSS), NO_λ is nitrogen oxidized (mg/l), nbVSS =nonbiodegradable Volatile Suspended Solids (mg/l), VSS_0 and TSS_0 =influent Volatile and Total Suspended Solids (mg/l)

Finally, 10 000 Monte Carlo simulations were performed on both methods to obtain a probability distribution model.

2.2.4 Municipal Solid Waste (MSW) estimations

MSW is an attractive source of energy because it otherwise has negative value (due to disposal costs), it is readily available in centralized locations, it has no competing uses (it would otherwise be landfilled) [109]. MSW has a high calorific value that is comparable to conventional biomass feedstocks. Lastly its suitability as a potential feedstock is supported by its immediate availability with an already established collection/transportation infrastructure and fee provided by the residents that does not exist for other feedstocks [110]. Due to its unique properties as a potential feedstock for HTC, a separate analysis of using this source is given in chapter 3.

2.2.5 Brewer’s spent grain (BSG) estimations

Due to its nutritional and functional properties, BSG is increasingly being considered as an adjunct for human consumption. The fortification of biscuits [111-114] pasta [115, 116] and other bakery products and snacks has been investigated [117]. The potential health benefits in BSG are derived from its fiber (e.g. AX, β-glucans) and phenolic (e.g. hydroxycinnamic acid) components. Therein lies the fundamental dilemma that constitutes the central issue here, which of the two options food or coal-alternative fuel production from BSG will have the least impact on the environment? A comparison of these two alternative uses of BSG will be given in chapter four.

2.3 Results and Discussion

2.3.1 Biomass from animal dung

A maximum of 7.3 million Mg/yr of animal dung resource is theoretically available for biofuel production, however, after accounting for the efficiency in collection and accessibility, this drops down to 4.4 million as shown in **Fig. 2.1**. Roughly 21.1-75.3 million GJ/yr. is potentially available but since farmers might prefer using dung as manure, only 0.43-45.0 million GJ can be exploited for bioenergy. Shonhiwa [102] reports a potential of 75.5 million and a sustainable 34.0 million (GJ/yr.) after considering other uses. Hemstock [55] suggests 4.5 million Mg/yr with an energy potential of 78.4 million GJ is hypothetically possible. The model here predicts a less than 5% chance of dung potentially providing more than 52.3 million GJ/yr rather less than 31 million GJ/yr can be provided.

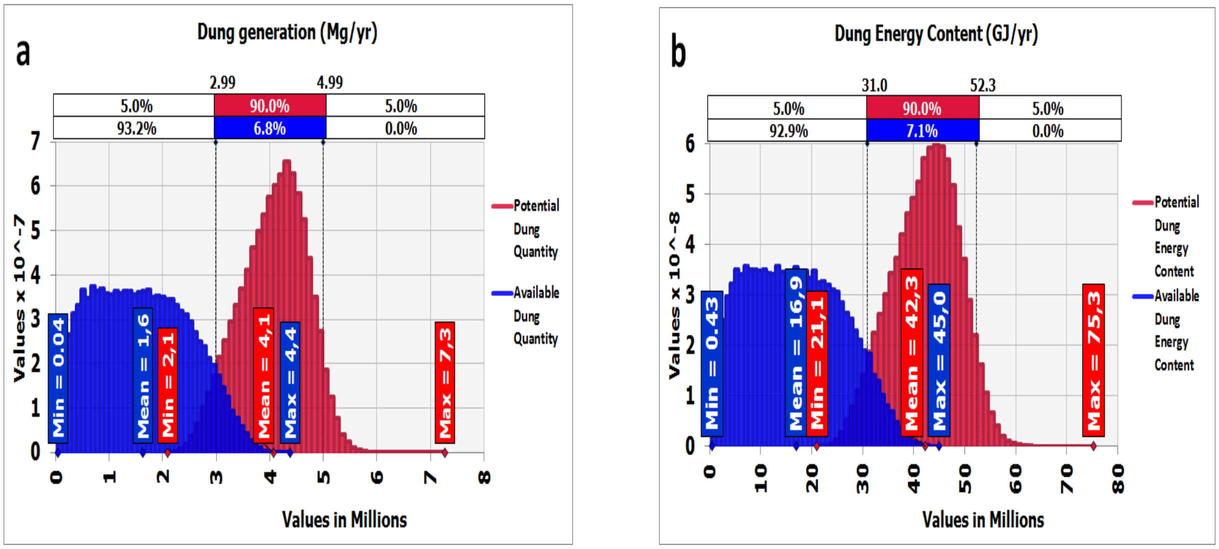


Fig. 2.2. Probability distribution model for a) dung generation b) dung energy content

Table 2.1 Summary of 100 000 Monte Carlo simulations for animal dung generation

Dung Type	A_D (000 Mg/yr.)			P_D (000 Mg/yr.)			Available Energy Content (000 GJ/yr.)		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Asses	22.7	89.0	2684.9	0.000	35.6	1392.7	0.003	370.6	14330.1
Cattle	1870.3	3545.6	4903.1	0.003	1418.1	3794.9	0.032	14749.9	40195.1
Poultry	0.0	0.4	318.2	0.000	0.2	127.9	0.000	1.7	1303.7
Goats	53.9	300.9	826.5	0.001	120.5	621.1	0.006	1252.9	6565.0
Horses	1.4	16.7	30.6	0.000	6.7	24.0	0.000	69.3	257.4
Mules	0.6	0.9	1.4	0.000	0.4	1.1	0.000	3.8	11.7
Pigs	14.0	47.5	132.1	0.000	19.0	98.9	0.004	197.2	1068.5
Sheep	36.2	65.9	127.9	0.000	26.4	99.2	0.001	274.5	1067.7
Combined	2093.2	4066.9	7268.4	41.97	1626.8	4380.5	431.6	16919.9	45006.0

At a 90% confidence interval, 2.98-4.99 million Mg/yr. of dung is generated (31.0-52.3 million GJ/yr.) and only 0.3-3.10 million Mg/yr. (3.4-32.3 million GJ/yr.) is available for biofuel production. Table 1 is a complete summary of the possible contributions from each category of livestock. Cow dung can be expected to be a major supply of this form of biomass as shown in Table 1.

2.3.2 Biomass from crop residues

The major crops considered in our model can be divided into 10 categories as shown in Table 2. The various crops include maize, wheat, and sorghum; groundnuts, soybeans, sunflowers, sugarcane, fruit crops, etc. each aggregated according to FAO's standards. From the theoretically possible range of 1.1-7.4 million Mg/yr. of crop residue, only about 0.14-5.4 million Mg/yr can be recovered and diverted to biofuel production. From the 90% confidence level shown in Fig. 2, 2.6-5.5 million Mg/yr. of crop residue is generated from which there is a very low probability (17%) for the actual available crop residue to be in the same range. These residues could potentially provide 36.2-85.5 million GJ of bioenergy at a 90% confidence level as shown in Fig 2 b. Jingura et al [8] estimated a potential of 86.4 million GJ from about 8.1 million Mg/yr of residues, falling well within the 5 % range of possibility given here. The previous potential estimates are based on deterministic modelling and do not take into account the uncertainties of agricultural productivity and imprecision that may be associated with the researcher's presuppositions. Sugarcane residues can be expected to play a huge role in the provision of suitable biomass for bioenergy production although there is great variability in supply as shown in Table 2. Owing to the high calorific value of its residue, it can provide nearly half of the combined energy potential of all crops.

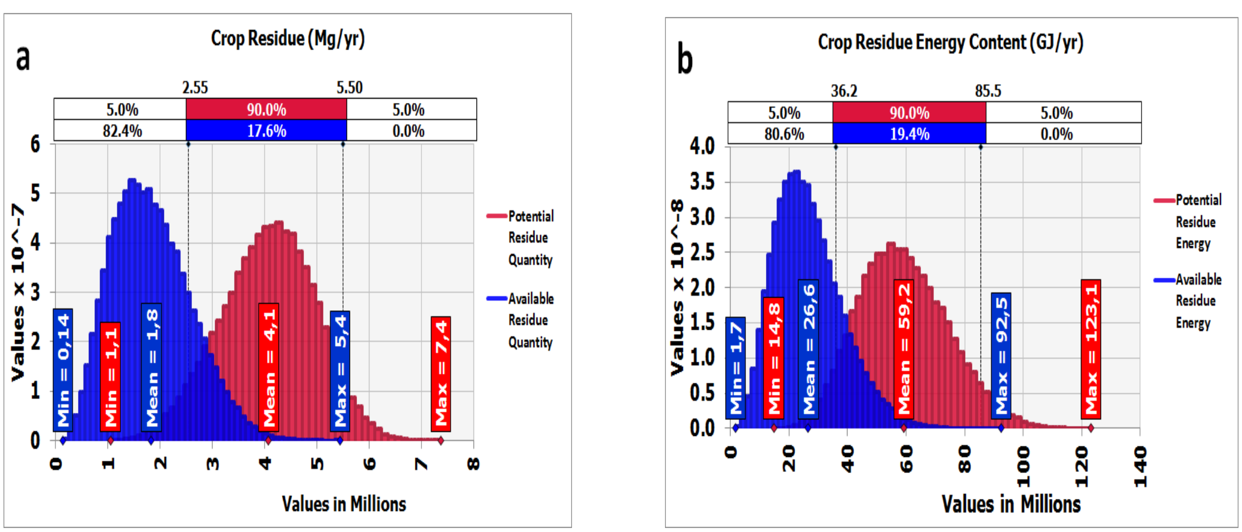


Fig. 2.3. Probability distribution model for a) crop residue generation b) crop residue energy content

From both Table 1 and 2 it is clear that there is a synergistic effect from sourcing biomass from all possible forms of biomass.

Table 2.2 Summary of 100 000 Monte Carlo simulations for crop residue generation

Residue Type	P_{CR} (000 Mg/yr.)			A_{CR} (000 Mg/yr.)			Available Energy Content (000 GJ/yr.)		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Cereals	226.6	1007.1	2101.6	0.002	453.5	1838.5	0.037	7450.1	32324.5
Citrus Fruit	12.2	53.4	94.6	0.000	24.0	84.7	0.002	271.1	1586.7
Coarse Grain	193.9	943.0	1949.8	0.005	424.0	1711.4	0.071	6964.9	30823.0
Fruit excl Melons	23.8	78.2	132.6	0.000	35.3	118.9	0.002	397.9	2250.9
Pulses	9.5	24.9	40.2	0.000	11.2	36.0	0.003	186.2	661.5
Roots and Tubers	17.6	43.3	94.6	0.000	19.5	82.3	0.001	89.6	442.1
Treenuts	0.0	0.6	213.9	0.000	0.3	165.8	0.000	3.6	2199.3
Vegetables & Melons	32.5	74.8	123.6	0.000	33.7	107.8	0.001	379.9	2078.9
Oilcakes Equivalent	0.6	114.8	231.5	0.342	51.7	203.2	5.671	1006.0	4913.2
Sugarcane	174.7	1737.4	3134.8	140.2	781.9	2749.7	2303.5	9893.2	52271.7
Combined	1053.4	4077.4	7377.2	141.1	1835.0	5445.7	1730.4	26642.5	92523.4

For example, the sum of probability distributions for each type of crop residue are less than the combined distribution function. This would suggest that any conversion process that would be implemented would need to be versatile enough to handle any type of raw biomass material. If there is a heavy reliance on just one particular feedstock, it may lead to production delays when there is a fall in the supply of that raw material. For sugarcane, that could be a drop from 2.7 to 0.14 million Mg, almost a factor of 20.

2.3.3 Woody biomass

Growing wood stock is roughly 0.75 to 1.36 billion Mg at a 90% confidence level. In 1985 and 1996, the total growing stock was estimated to be 1.4997 and 1.168 billion Mg respectively [106]. As shown in **Fig. 2.4**, the total wood cut is 12.8 million/yr. on average. From the mass balance, the infield residue and process residue are estimated to be 3.7 and 1.2 million bone-dry Mg/yr respectively. This contrasts findings of [118] and [55] , who reported 0.75 million (saw dust waste) and 2.3 million (forestry wastes) respectively. However, their estimates are well within the range given in our study.

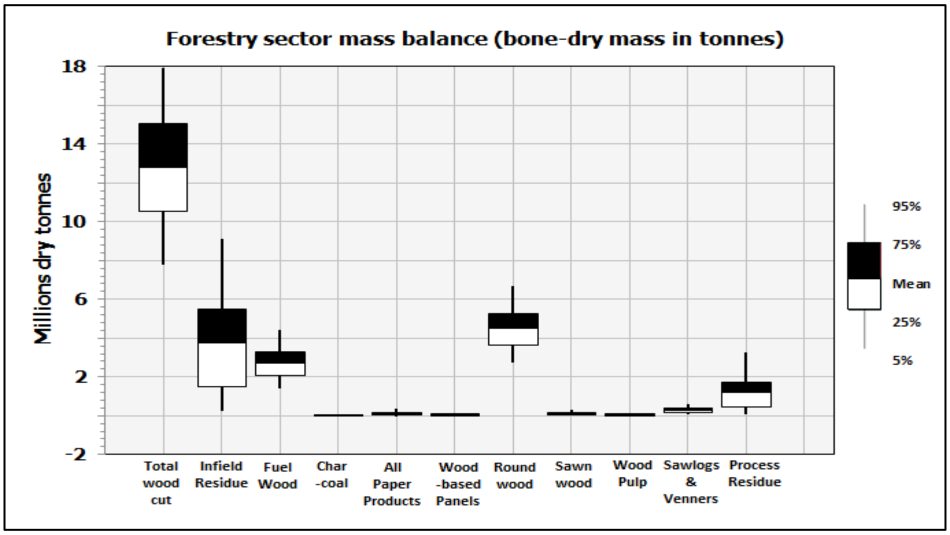


Fig. 2.4 Box plot of annual forestry sector mass balance

Fuel wood ranges from 1.41-4.44 bone-dry Mg/yr at a 90% confidence level. Other studies suggest 4.7-6.0 million Mg [55, 102]. It must be noted that [55] assumes a wood density at 20% air dry moisture whilst it is not clear in the other investigation. Green wood can have a variable moisture content well above 30%. The study here indicates that the efficiency of roundwood (removals) to final useful products conversion is very low, about 6.1-24.8% at a 90% confidence level (with a maximum of 58.6%). This concurs with [119], who asserts that the commercial wood conversion (from harvesting to finished products) is roughly 20% efficient. As a result, waste in the form of sawdust, rough cut slabs, etc. is available in large quantities and can be exploited for bioenergy production.

2.3.4 Sewage sludge

At a 90% confidence level, between 3067-179 110 Mg/yr of dry sewage sludge is produced as shown in Fig.1. The model predicts 59,800 Mg/yr (Method 1) and 42,000 Mg/yr (Method 2) of sewage sludge on average. This amounts to a mean of 0.75 PJ and 0.5 PJ under Method 1 and 2 respectively that can potentially be exploited. If Zimbabwe attains levels of wastewater service quality of developed countries, roughly 152,000 tons/yr (1.9PJ) is available for the current urban population. There is some potential in sludge-to-energy, however the economics of the process must be assessed for a more conclusive answer.

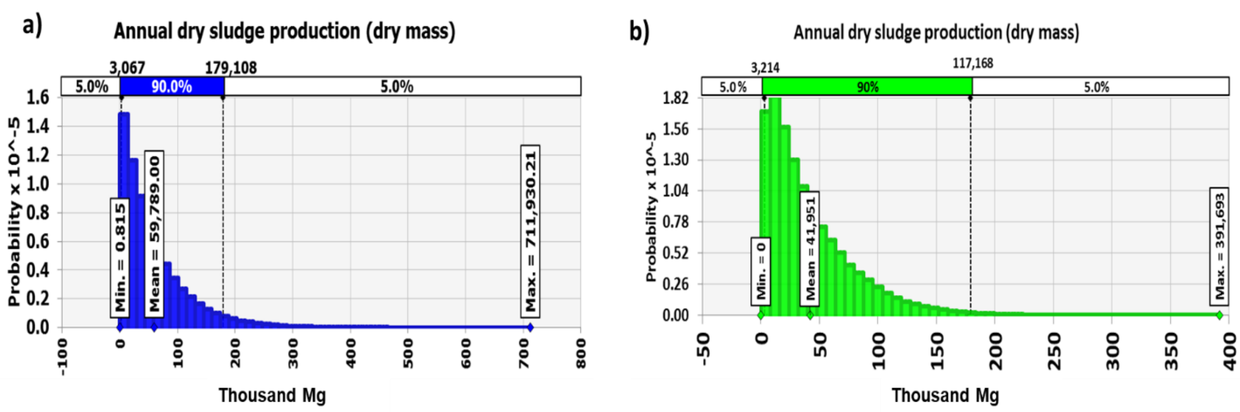


Fig 2.5 Estimated annual sewage sludge production (dry metric tons) using a) Method 1 and b) Method 2

2.4 Conclusion

Bioenergy production from the quantities of residues estimated in this study suggests a lower potential than previous estimates. It is evident from the stochastic model presented that deterministic models are like seeing only one side of the coin. The findings in this study indicate that previous research on the exploitable quantities of biomass in Zimbabwe were too optimistic. A 90% confidence interval estimate of the agricultural biomass generation rate is 2.55-5.49 million and 2.98-4.99 million Mg/yr. for crop residue and dung respectively. From this, an annual mean of 1.8 and 1.6 million Mg of crop residue and dung respectively can reasonably be expected to be available to produce biofuels. Two unrelated methods were used to estimate dry sewage sludge production rate. At a 90% confidence level, the model predicts 59800 tons/yr (Method 1) and 42000 tons/yr (Method 2) of sewage sludge on average. This amounts to a mean of 0.75 PJ and 0.5 PJ under Method 1 and 2 respectively that can potentially be exploited. The infield residue and process residue (woody biomass) are estimated to be 3.7 and 1.2 million bone-dry Mg/yr respectively.

From the foregoing, it is clear that versatility is needed in any envisaged thermochemical technologies to counteract the variability in the feedstock supply. Further research on the economic viability of biofuel production in Zimbabwe is also needed to ascertain the level of business success that can be expected by both the private sector or government for any bioenergy projects. This research can be a stepping stone to such endeavors.

Chapter 3: Effect of coal-alternative fuel production from MSW via HTC on atmospheric pollutant emissions

In this chapter, the environmental impact of coal-alternative fuel production from Zimbabwe's MSW using HTC and subsequent usage in power stations is explored. In this chapter, the focus is on greenhouse gas emissions.

3.0 Introduction

The collection of ZMSW is confined to the urban population of about 5.38 million people, albeit with meagre resources available for a majority of local authorities, the waste management system still leaves a lot to be desired. Local authorities' capacity to collect, process and dispose of waste is limited because of inadequate infrastructure, political priority and awareness [46]. Refuse compactors, for example, are constantly in a state of disrepair and more often than not, councils have to resort to the use of inappropriate equipment such as tractors to ferry waste to dumpsites [31]. It is worrying to note that despite council's contention with illegal dumpsites, observers claim to have witnessed council tippers divert waste to open gravel pits in close by farms instead of legal dumpsites [47]. Moreover, a study by [38] reveals that the final disposal of ZMSW is not ecologically sound as 98% of all legally operated landfills are not sanitary. These 'landfills' are not suitably maintained and due to a lack of daily cover, are exposed to the wind and rodents which scatter the waste. They are also a fire hazard; a serious fire broke out in October 2013, burning for two weeks and leading to one fatality [44].

There are contentions between urban dwellers and municipalities due to the growing complexity of ZMSW composition. In the second largest city, Bulawayo, local authorities refuse to collect disposable diapers from residents [12]. Another emerging issue is the current state of the healthcare sector's waste disposal practices. Incinerators at both the public and private clinics are either absent or dysfunctional [120]. Dumping in rivers is commonly opted for by Zimbabwe's industrial sector, further worsening the negative impacts on the environment [121]. The collection of ZMSW in urban areas is mostly irregular with most high-density areas going for long periods without the collection of their waste. This inevitably prompts more illegal dumping and rampant burning of waste as the locals take matters into their own hands [46]. Mandevere [47] reveals that inhabitants of low-density areas in Harare, the capital, have resorted to privately hiring collectors or alternatively transporting their own waste to a local disposal site independently as they have the financial capacity to do so. As a result, the full brunt of the substandard waste management system is felt more by urban dwellers in high density areas compared to their low-density counterparts. Scenes of heaps of illegally dumped litter compounded by public urination, open defecation and sewage sludge from burst pipes have become a trademark for these low-income high-density areas [30, 35, 46].

To assess the impact of an HTC waste management strategy for Zimbabwe, it is necessary to identify the nature and composition of the country's waste. There is spatial and temporal variation in MSW composition and generation rates. Therefore, as part of our attempt to implement an HTC waste management system, the statistical analysis of the reported MSW characteristics spanning different locations, income levels and time is an essential step. Among researchers there is a clear consensus about the positive correlation between MSW generation rates and economic status for developing nations [122]. An improvement in Zimbabwe's economic growth alongside rapid urbanization is likely to surge MSW generation rates even higher and an alternative strategy to avert the imminent social and environmental problems associated with rising MSW quantities will be needed. Hydrothermal treatment of waste could be an effective solution for converting this waste into a resource thereby creating a much cleaner environment. [57, 123-129] conducted extensive research on MSW conversion to hydrochar. There is widespread knowledge on the chemical nature and economic viability of this process [14, 130]. There are also reports on real world applications of the technology [28, 131, 132]. However, a gap exists in the scientific literature on the environmental impact of a large-scale HTC system.

3.1 Materials and Method

3.1.1 System scope of modelled coal-alternative fuel production from ZMSW

The process of production of coal-alternative fuel (ZMSWH) from ZMSW is executed within several operations as shown in **Fig. 3.1**. The first stage involves the conversion of ZMSW to an organics fraction after the removal of metals, glass, ceramics (incombustibles), etc. This is essentially a heavy fraction of small-sized particles containing organics, plastics, wood, rubber, etc. This fraction, ZFOMSW is placed into the hydrothermal carbonization reactor and converted into ZMSWH (hydrochar). Within the discussed system of ZMSWH production from ZMSW, the environment, in terms of direct pollutant emissions, is affected by the following processes: collection and transportation of ZMSW and ZMSWH (diesel fuel combustion in vehicles), shredding of ZMSW (diesel consumption), ZOFMSW hydrothermal carbonization (energy coal-fired boiler) and receiving area operations (diesel fuel combustion). Other unit operations consume electricity and pollutant emissions are mainly from power generation at the coal-fired stations. The methodology of the research involved the collection of data on ZMSW characteristics, general MSW properties and Zimbabwe's thermal power generation from previous studies for the development of a numerical model for estimating a) the quantity of ZMSW generated and its composition b) the quantity and composition of ZOFMSW c) the potential amount of ZMSW derived hydrochar (ZMSWH) available for co-firing d) emissions from the hypothetical co-burning of ZMSWH in Zimbabwe's thermal power stations. This entailed the estimation of emissions related to ZMSW collection, its conversion to ZMSWH, coal-mining and hypothetical co-combustion with ZMSWH so that a full environmental impact of this waste to biocoal system could be ascertained.

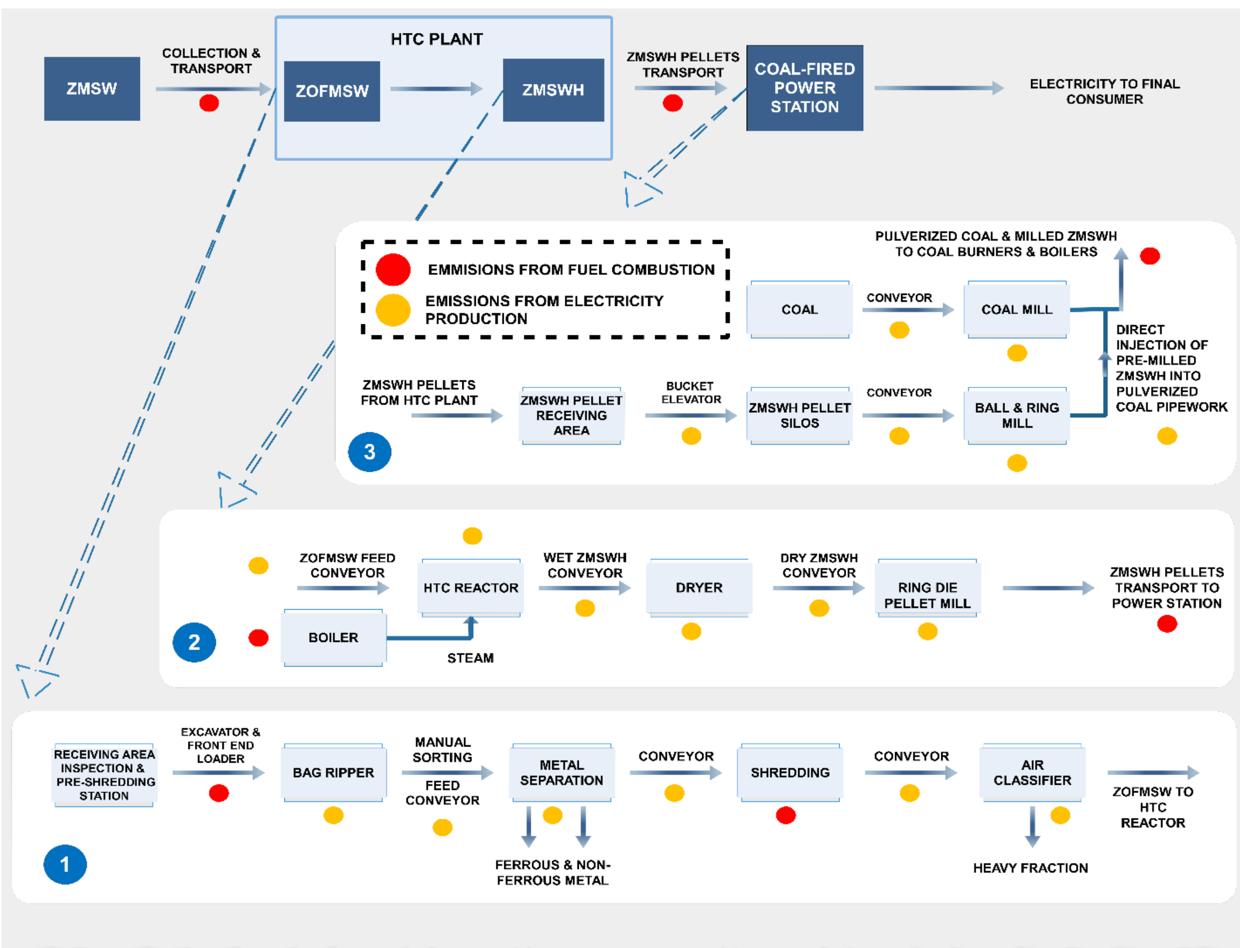


Fig. 3.1 Overview of coal-alternative fuel production

3.1.1.1 Model limitations

Some comments are warranted on the limitations of our model. Given the scale and complexity of an HTC based waste-to-energy system our simplified model cannot fully capture all parameters. For example, HTC produces gases and aqueous chemicals, in addition to the desired solid product. A commercial HTC plant would have to recirculate and/or properly dispose of its process water to reduce its impact on the environment. This prerequisite adds to the cost, complexity, and emissions of any waste-to-energy system that employs HTC technology. We did not make any estimations on either the amounts or quantities of other product streams. Coal usage and its associated toxic emissions (trace metals like mercury) and trace organics (e.g., dioxins) were not modelled. Despite the envisaged environmental benefits, the capital costs could possibly be a hurdle, particularly for HTC which is not yet widely established. Due to a gap in literature in terms of emission factors for these other streams, their estimations could also not be justified.

3.1.2 Estimation of the quantity and composition of ZMSW

An estimation of ZMSW generation rate was determined by using GDP per capita (current US$) data from 2012 [133] and MSW generation rates of 38 low income countries reported by [134]. The underlying assumption is the correlation between GDP per capita and MSW generation rate. A linear relationship between the two variables was assumed so that Zimbabwe's current MSW generation could be ascertained. Regression analysis was carried out on the data. This estimate was averaged together with the reported values shown **Table 3.1**. The collectable ZMSW was found by applying the formula:

MSW collected annually = MSW generation per capita (kg/capita/day) × Total Urban Population × 365 days × Collection Efficiency (3.1)

Mean collection efficiencies were reported to be 63.9% [38] and 85.2% [50] hence an average value of 74.6% was assumed. The composition of ZMSW was ascertained by statistically analysing data from previous field studies on ZMSW shown in **Table 3.2**. The total population of Zimbabwe is estimated to be 17.09 million with 31.4% living in urban areas [135]. ZMSW is collected in urban areas only.

3.1.3 Energy content, proximate and ultimate analysis of ZMSW

In order to determine the proximate analysis and ultimate analysis of ZMSW on a dry basis, an estimate of the moisture content was carried out. The moisture and energy content of ZMSW was calculated using mid-values of the typical range of values shown in Table 3.3. The proximate and ultimate analysis of ZMSW was then predicted using mean values reported in literature which are summarized in **Table 3.4.**

An estimation of the energy content of the ZMSW was obtained by using average heating values and verified with the Modified Dulong Formula.

$$\text{Energy content (KJ/kg)}, E = 337C + 1428 (H - O/8) + 95S \qquad (3.2)$$

In order to validate our results, our simulated ZMSW energy content, proximate and ultimate composition was compared to field data reported by [145]. The methane potential of ZMSW was determined by using the Intergovernmental Panel on Climate Change (IPCC) default method [146] which assumes that all potential methane is released in the year the MSW is discarded. This is unrealistic but it will provide a basis for drawing comparisons between some scenarios in subsequent sections of this paper. The equation for estimating methane potential is given by;

$$\text{Methane emissions (Gg/yr)} = (MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times (16/12)-R) \times (1-OX) \qquad (3.3)$$

where MSW_T is total MSW generated (Gg/yr), MSW_F is fraction of MSW disposed to solid waste disposal sites, MCF is methane correction factor (fraction), DOC is the degradable organic carbon (fraction) (kg C/ kg SW), DOC_F is the fraction DOC dissimilated, F is the fraction of methane in landfill gas, 16/12 represents the conversion of C to CH_4, R is the recovered CH_4 (Gg/yr) and OX is the oxidation factor

Default values were used except for MSW_T, MSW_F, MCF and DOC (carbon content not originating from plastics but from organic biodegradable waste) which were determined from the model. R was assumed to be 0 as the recovery of LFG is not practiced in Zimbabwe. MSW_F was assumed to be equal to be 100% (due to predominantly poor solid waste management, landfills and open dumps are not so different) and MCF was taken as 0.4 for unmanaged, shallow sites (<5m).

Table 3.1 Reported MSW waste generation rates for Zimbabwe (Africa)

MSW Generation Rate (kg/capita/day)	Reference
0.70	[136]
0.50	[137]
0.50	[51]
0.53	[134]
0.31	[138]
0.50	[50]
0.79	[139]
0.29	[140]
0.53	[52]
0.44	[141]
0.60	[142]
0.42	[38]
0.64	[143]
0.70	[144]
0.64	[143]
0.64	This study
0.54±0.08	**Overall average**

3.1.4 Estimation of the quantity and characteristics of ZOFMSW

The process flow and equipment for converting ZMSW to ZOFMSW is shown in **Fig. 3.1.** The mass of each ZMSW component, i, remaining after its removal by each unit operation, j_n, is calculated by multiplying its total weight input by the separation efficiencies of each equipment j_n as shown in equation 4. The separation efficiencies are organized in a matrix as shown in **Table 3.5.**

$$W_{i_n} = m_{i_{in}} \cdot (f_{j_1} \cdot f_{j_2} \cdots f_{j_n}) \qquad (3.4)$$

W_{i_n} is the mass of waste fraction i remaining after passing through equipment j_1 to j_n (Mg)
$m_{i_{in}}$ is the initial mass of waste fraction i to be processed (Mg)
f_{j_n} is the percentage of waste fraction remaining after passing through equipment j_n (%)

Once the mass components for ZOFMSW were calculated, the proximate, ultimate and energy content were predicted using **Tables 3 and 4.** Emissions emanate from the shredders driven by a diesel powered 600HP engine. In the receiving area, a mobile pre-shredder unit will be used for the tearing pre-shredding of very large ZMSW components. Fuel Consumption for a 600HP diesel engine power was calculated using equation 5.

Fuel consumption. L/hr = (specific fuel consumption (kg/(kWhr)) × rated engine power (kW)) ×engine load factor/Fuel Specific Weight (3.5)

The specific weight of diesel is 0.84 kg/L [149] and specific fuel consumption rate for many diesel engines lies between 0.21 to 0.26 kg/(kWhr) [150]. The shredders are assumed to operate for 4380 hr/yr (12 hr/day × 365 days). From the volume of diesel combusted. the following emission factors were used to estimate pollutant air emissions. For every litre of diesel combusted, 2.70 kg of CO_2 [151], 0.07g of NO_X [152], 4.72g of SO_2 [153] and 0.15g of CH_4 [152] are released.

Table 3.2 Reported composition of ZMSW

Location	Paper & Cardboard	Glass & Ceramics	Metals	Plastics	Leather & Rubber	Textiles	Yard Waste & Sweepings	Wood	Putrescibles	Miscellaneous	REFERENCE
	MSW COMPONENTS (%)										
HARARE											
	30.0	10.0	10.0	10.0	5.0	5.0	0.0	5.0	5.0	20.0	[41]
Sunningdale	11.7	0.8	0.8	6.8	0.3	2.1	0.0	0.6	75.9	0.8	[41]
Mabelreign	13.5	2.3	1.1	8.0	0.0	1.1	0.0	0.3	73.6	0.2	[41]
Borrowdale	23.1	6.5	4.0	11.7	0.4	3.8	0.0	0.7	47.7	2.3	[41]
Glenview Area 8	22.0	5.0	10.0	25.0	0.0	12.0	0.0	0.0	22.0	4.0	[35]
Mbare	6.0	2.0	12.0	11.0	0.0	4.0	16.0	0.0	28.0	21.0	[49]
	16.1	2.8	3.8	26.4	0.0	1.5	17.6	0.0	14.3	17.5	[53]
Borrowdale	35.0	4.0	3.0	18			1.0	9.0	15.0	15.0	[47]
Gunhill	32.0	5.0	4.0	16			2.0	8.0	18.0	15.0	[47]
Mandara	33.0	4.0	3.0	16.5			2.5	8.0	17.0	16.0	[47]
Westlea	30.0	6.0	5.0	22			7.0	10.0	15.0	5.0	[47]
Milton Park	31.0	2.0	2.0	21			6.0	8.0	26.0	4.0	[47]
Waterfalls	29.0	4.0	3.0	20			9.0	7.0	23.0	5.0	[47]
Mbare	10.0	1.0	5.0	9			2.0	9.0	54.0	10.0	[47]
Budiriro	14.0	2.0	4.0	10			1.0	9.0	49.0	11.0	[47]
Highfield	13.0	3.0	3.0	8			2.0	9.0	55.0	7.0	[47]
BULAWAYO											
	30.0	0.4	0.6	42.0	0.0	0.0	4.0	0.0	23.0	0.0	[10]

	20.0	5.0	10.0	10.0	3.0	2.0	0.0	5.0	10.0	35.0	[147]
GWERU											
CBD	5.0	0.0	3.0	37.0	0.0	0.0	10.0	0.0	42.0	3.0	[33]
Monomotapa	10.4	3.5	30.6	5.0	5.0	9.0	0.0	10.4	10.7	15.4	[31]
Shamrock Park	10.3	5.0	39.6	5.7	3.0	1.0	0.0	12.1	6.4	16.9	[31]
Mkoba	17.1	5.0	18.3	4.5	4.0	8.0	0.0	13.0	20.7	9.4	[31]
Kudzanai/ Kombayi	14.8	3.0	6.1	7.2	1.0	2.0	0.0	1.9	57.1	6.9	[31]
Ascot	18.6	3.3	5.0	6.4	5.6	4.0	0.0	17.0	31.6	8.5	[31]
MASVINGO											
	11.0	0.0	5.4	9.0	1.1	2.1	0.0	0.0	70.4	1.0	[30]
Mucheke	30.0	5.0	4.0	40.0	0.0	0.0	0.0	0.0	15.0	6.0	[34]
VICTORIA FALLS											
	34.0	6.0	5.0	15.0	2.0	4.0	0.0	0.0	26.0	8.0	[37]
MUTARE											
Sakubva	27.0	5.0	6.0	23.0	0.0	3.0	3.0	1.0	32.0	0.0	[36]
CHINHOYI											
Low Density	18.7	8.9	3.0	6.4	9.3	5.4	0.0	0.0	43.3	5.0	[148]
High Density	10.3	4.0	1.0	3.0	7.7	2.1	0.0	0.0	56.1	15.5	[148]
	12.0		15.0	28.0			4.0		40.0	1.0	[39]
CHEGUTU											
Mubaira CBD	20.0	13.3	0.0	25.4	0.0	0.0	33.3	0.0	8.0	0.0	[40]
Mubaira Residential area	17.1	0.0	0.0	28.6	0.0	0.0	14.3	0.0	40.0	0.0	[40]

Table 3.3 Typical moisture content and energy content of MSW components

Component	% moisture content		Energy content (MJ/kg)	
	Range	Typical	Range	Typical
Food wastes	50 – 80	70	3.5 – 7.0	4.7
Paper	4 – 10	6	11.6 – 18.6	16.7
Cardboard	4 – 8	5	14.0 – 17.4	16.3
Plastics	1 – 4	2	27.9 – 37.2	32.6
Textiles	6 – 15	10	15.1 – 18.6	17.4
Rubber	1 – 4	2	20.9 – 27.9	23.3
Leather	8 – 12	10	15.1 – 19.8	17.4
Garden trimmings	30 – 80	60	2.3 – 18.6	6.5
Wood	15 – 40	20	17.4 – 19.8	18.6
Glass	1 – 4	2	0.1 – 0.2	0.1
Tin cans	2 – 4	3	0.2 – 1.2	0.7
Nonferrous metals	2 – 4	2	0	0.0
Ferrous metals	2 – 6	3	0.2 – 1.2	0.7
Dirt, ashes, brick, etc.	6 – 12	8	2.3 – 11.6	7
Municipal solid waste	15 – 40	20	9.3 – 15.1	10.5

Source: [154]

Table 3.4 Mean values for proximate and ultimate analysis of MSW components

Component	Proximate Composition (Dry Basis)			Ultimate Composition (Dry Basis)								
	Ash	**VM**	**FC**	**C**	**H**	**N**	**Cl**	**S**	**O**	**P**	**F**	**Br**
Paper& Cardboard[1]	7.19	71.29	19.26	43.72	6.03	2.87	0.13	0.13	40.00	0.00	0.00	0.00
Metal, Glass & Ceramics[2]	100.00	0.00	0.00	0.00	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Plastics[3]	2.88	90.28	2.60	71.97	9.38	0.50	5.71	0.20	7.28	0.00	0.00	0.00
Leather, Textiles & Rubber[4]	7.10	79.76	9.93	55.48	7.19	3.31	0.69	0.52	31.16	0.00	0.00	0.00
Yard Waste & Sweepings[5]	5.65	55.03	13.51	47.10	5.96	2.31	0.37	0.21	37.75	0.00	0.00	0.00
Wood[6]	1.53	77.23	14.54	49.07	6.02	0.31	0.10	0.08	42.88	0.00	0.00	0.00
Putrescibles[7]	4.61	60.97	7.61	52.14	7.51	2.06	0.80	0.23	31.53	0.00	0.00	0.00
Miscellaneous[8]	20.77	58.14	9.96	39.08	4.76	1.58	0.63	0.42	27.75	0.40	0.01	0.00

Sources

[1, 3, 4] [155-159]

[2] [157]

[5, 6] [155, 157-159]

[7] [155-160]

[8] [110, 157, 159, 161-164]

Table 3.5 Percentage of Waste Component retained (i) after passing through unit operation(j)

Waste Component (i_n)	Equipment (j_n)					
	Bag Ripper[a] (j_1)	Manual Sorting[b] (j_2)	Magnet[c] (j_3)	Eddy Current Separator[d] (j_4)	Shredder[e] (j_5)	Air Classifier[f] (j_6)
Paper & Cardboard **(i_1)**	100	95	100	100	100	85-99
Metal (Ferrous) **(i_2)**	100	95	12	100	100	2-10
Metal (Non-ferrous) **(i_3)**	100	95	100	13	100	45-65
Glass & Ceramics **(i_4)**	100	95	100	100	100	2-10
Plastics **(i_5)**	100	95	100	100	100	85-99
Leather, Textiles & Rubber (i_6)	100	95	100	100	100	85-99
Yard Waste & Sweepings **(i_7)**	100	95	100	100	100	85-99
Wood **(i_8)**	100	95	100	100	100	85-99
Putrescibles **(i_9)**	100	95	100	100	100	85-99
Miscellaneous **(i_{10})**	50	95	80	80	100	85-99

a – Assume 50% of components in the miscellaneous category are combustible and remaining is left in the yard after inspection

b – Assume 5% of each component of ZMSW is out of specifications or not suitable for conversion as determined during manual sorting

c,d – Based on mixed-waste material recovery facilities (MRF) Separation Efficiencies reported by [165]. Assume equal distribution of ferrous and non-ferrous metals in the 'metals' category

e – Assume no loss of material in this unit operation

f – Based on the report by [166]. ZMSW is separated into a light fraction ("lights") that contains an abundance of combustible material, ZOFMSW, and a heavy fraction ("heavies") that is mostly inorganic in nature.

3.1.5 Estimation of the yield and composition of ZMSWH

In this paper we wish to use a simple model to predict the quantity and elemental composition of ZMSWH. This may seem at odds with the highly complex nature of hydrothermal carbonization. Even with the vast amount of research on the topic, the mechanisms and kinetics involved in the process are still not fully understood [167]. After sifting through some papers in the literature, the work by [168] and [169] stood out.

Table 3.6 Model and assumptions for predicting the properties of ZMSWH

Component	Basis for prediction	Reference
C	Regression tree model associated with hydrochar carbon content (%, dry wt.)	[168]
H	23% reduction in H/C atomic ratio from MSW to hydrochar at 210℃ and 60-minutes residence time	[169]
O	45% reduction in O/C atomic ratio from MSW to hydrochar at 210℃ and 60-minutes residence time	[169]
N	Assume 50% reduction from solids	[169]
S	Assume 37% reduction from solids	[169]
Cl	80% of initial Cl can be removed to produce a solid fuel with low chlorine content	[170]
Ash	By difference: Ash% = 100% – C% – H% – N% – S% – O%	
Calorific Value	1. Regression tree model associated with hydrochar energy content (kJ/g dry solids) 2. Dulong Formula	[168]
Hydrochar yield	1. Regression tree model associated with solid yield (%, dry wt.) 2. Li et al equation (See equation 7) 3. Lin et al equation (See equation 6) Average value of the results from these 3 equations was used as the yield in our model	[168] [169]

Through the development of multiple linear regression and regression tree models (based on experimental data on the carbonization of MSW and other forms of biomass), the researchers were able to model product characteristics based on the process conditions and feedstock chemical properties very well. Multiple regression analysis is particularly useful for simulating experimental data [171]. [169] developed a multiple regression model for predicting MSW-derived hydrochar, iterating the findings from [167, 168] that hydrochar properties depend on both process conditions (temperature and residence time) and feedstock properties (e.g., carbon content). Results from experiments indicate that hydrochar and gas yields are more strongly influenced by temperature than by residence time. **Table 3.6** provides a summary of how ZMSWH properties were predicted. With a rise in temperature, the H/C and O/C atomic ratios decrease causing the hydrochar to exhibit similar characteristics to lignite. The lower H/C and O/C atomic ratios presumably lead to lesser emissions, moisture contents and energy losses in the combustion process [172].

From [169] multiple regression model, the yield of hydrochar, Y_{solid}, can be predicted by;

$$Y_{solid}\ (\%,\ db) = -0.7817T + 0.001153T^2 - 0.2561t + 0.000475t^2 + 0.0004888Tt + 192.8 \qquad (3.6)$$

Their model identifies reaction temperature (T) and residence time (t) as the main influencers of solid yield. [168] has more parameters and is influenced by feed properties (ZOFMSW proximate and ultimate composition in our case) as well experimental conditions.

$$\text{Solid yield } (\%,\ db) = -1.12Ash_{feed} - 1.22VM_{feed} - 1.58FC_{feed} + 1.63C_{feed} - 4{:}89H_{feed} - 0.73O_{feed} + 0.43Solids_{initial} - 0{:}21T_{final} + 9.70\ (HT/t) + 1.36HR - 22.19VR + 212.76 \qquad (3.7)$$

where C_{feed} = carbon content of the ZOFMSW (%); H_{feed} = hydrogen content of ZOFMSW (%); O_{feed} = oxygen content of ZOFMSW (%); Ash_{feed} = ash content of ZOFMSW (%); VM_{feed} = volatile matter content of ZOFMSW (%); FC_{feed} = fixed carbon content of ZOFMSW (%); $Solids_{initial}$ = initial feedstock concentration (%, solid); T_{final} = final reaction temperature (℃); t = reaction time (min); HT = heating time (min); HT/t = heating time to reaction time ratio; HR = heating rate (℃/min); V = volume (mL); VR = volume ratio.

We assumed experimental conditions of t = 60.00 min, HR = 7.00 ℃, HT= 70.00 min, HT/t =1.17

V = 250.00 ml, VR = 0.90. HTC experimental results are representative of those obtained at a different reactor scale when scaling up [173].

Emissions from this stage, emissions are expected from the coal-fired boiler producing steam entering the hydrothermal carbonization reactor (**Fig. 3.1**). The formation of hydrochar was found to have a total energy requirement of 2.2 MJ/kg of MSW on average [128]. This helped to estimate coal requirements and associated emissions related to ZOFMSW conversion to ZMSWH. The quantity of CO_2 and SO_2 from ZMSWH combustion was predicted from its elemental composition (e.g. $C + O_2 \rightarrow CO_2$, $S + O_2 \rightarrow SO_2$). The calculated fossil carbon and biogenic carbon ratio was used to determine amount of carbon dioxide emitted.

3.1.6 Emissions estimates from Zimbabwe's coal-fired power stations

Annual coal consumption was estimated and emission factors applied to this estimate to quantify emissions from thermal power generation. Zimbabwe's thermal power plants are old and inefficient and breakdowns are frequent; the installed and dependable capacities are shown in **Fig. 3.2**. Dependability is attributed to a combination of ageing power plants which have suffered years of neglect and minimal maintenance, and inconsistent coal supplies as well as problems with the transmission and distribution network. The hours of operation are significantly reduced due to factors such as breakdowns and unreliable coal supply. Co-firing would not be expected to improve the dependability. In terms of installed capacity, we are assuming the plants are operating closer to their actual nameplate capacity but with similar hours of operation to dependable capacity. Emissions related to coal use were estimated for two scenarios; dependable and installed capacity. A quick estimate can reveal the quantity of coal required for producing 1 MW per year. Energy conversion takes place in two stages; the first part of the conversion depends on the efficiency of the boiler and combustion. About 88 % on a higher heating value basis is the normal range for a well-optimized power plant. However, [174] reports a value of 70% for a Zimbabwean plant. The second part is the steam cycle efficiency.

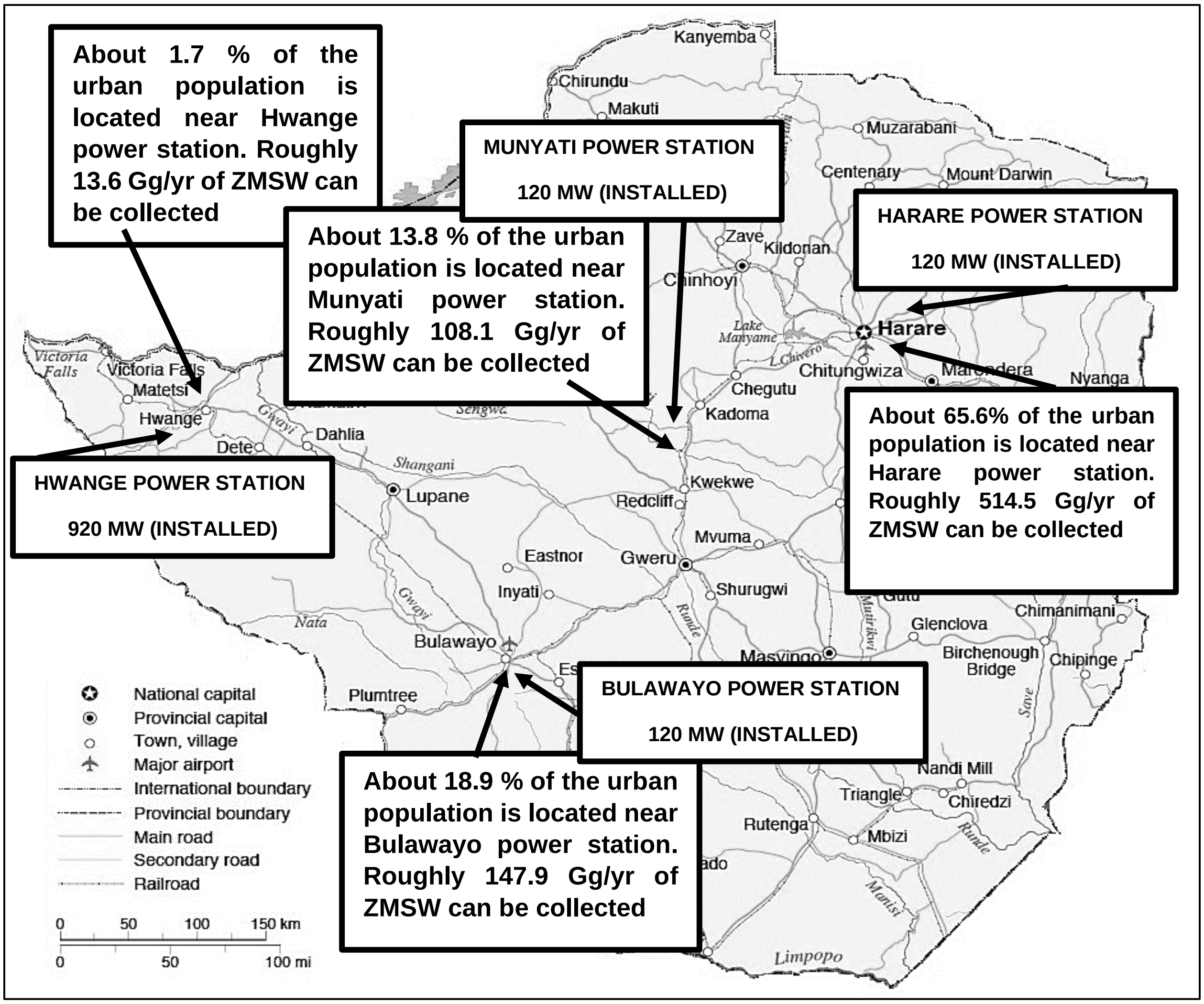


Fig. 3.2. Installed and dependable capacities of Zimbabwe's thermal power stations and relative distribution of the urban population.

Source: Power plant capacities taken from [174] and ZMSW estimation based on our calculations

Modern Rankine cycle, adopted in coal-fired stations, have efficiencies that vary from 32 - 42 %. This is governed mainly by the steam parameters. Higher steam pressure and temperatures in the range of 600 °C and 227 atm achieve a 42 % efficiency. Taking the lower value of 32%, the overall conversion efficiency (30% x 70%) is assumed to be 21%.

Table 3.7 Zimbabwe steam coal properties [174, 175]

Property	Reported Value	Values used in our model
Total Moisture %	3.6 - 6.4	5.00
Ash %	1.5 - 12.4	
Volatile Matter %	19.3- 42	
Fixed Carbon %	23.8 - 66.7	
Gross Calorific Valve (MJ/kg) Net Calorific Value (MJ/kg)	13.87 -32.08, 24.2 – 29.9 22.9-28.4	25.45
Carbon % Nitrogen % Sulphur %	68.3 – 76.5 1.72-1.88 0.15 -4.67	73.77 1.77 2.41

Table 3.8 Summary of MSW transportation and coal haulage parameters

Parameter	Average Value	Reference
Average annual distance travelled by refuse truck	40,234 km	[176]
Fuel Economy of refuse truck	0.92 km/L	[176-179]
Fuel Economy of diesel train (1980 -2015)	99 ton-km per L	[180]
Lifetime mileage-weighted average air pollutant emission factor for diesel refuse trucks	7.09 g/km for NO_X 0.09 g/km for SO_X 0.02 g/km for CH_4	[181]
Emission Factors for Diesel Heavy Truck	0.87kg/L for CO_2	[182]
Emission factors for diesel locomotives (uncontrolled)	0.04437 kg/L for NO_X 0.0000167 kg/L for SO_x	[183]
Carbon Dioxide Emission Factors for Diesel Fuels Methane Emission Factors for Non-Highway Mobile Combustion	2.68kg/L 0.18g/L	[184]

The plants typically use 20-30% of the energy input according to [174]. The heat rate or heat input required to produce one unit of electricity (1 kWhr), if the energy conversion is 100 % efficient, would be 3600 kJ. After considering the overall conversion efficiency, 17,142 kJ/kWhr (3600/21%) is required. Zimbabwe steam coal has an average heating value of 25.45 MJ/kg (refer to **Table 3.7**), therefore to produce 1 kw.hr, 0.673 kg of coal (17.14 MJ/25.45 MJ/kg) is required. A specific coal requirement of 0.673 Mg/MW.hr is our estimate. On a yearly basis this is 5,892 Mg/MW. However, according to (Kaseke, 2014) electricity is available from the grid only 62.75% of the time (out of 8,760 hours per year) due to plant shutdowns, meaning 3,552 Mg of coal per MW are required per year. All plants are assumed to operate for 5497 hrs per year. Using this figure, coal consumption estimates under installed and dependable capacity can be ascertained.

The emissions estimates are in three parts; coal mining, transportation and combustion. Emissions from coal transport were based on emission factors, average fuel economy of diesel trains shown in **Table 3.8** and haulage distances. Coal is conveyed to Hwange station by an overland conveyor belt which is 6 km long from Hwange Colliery hence it was not regarded in this estimate. Coal is hauled by rail from Hwange Colliery to Munyati power station, approximately 618 km away. Harare Power station and the colliery are a distance of 812 km apart. Bulawayo power station is roughly 314 km away. Emissions related to the mining of coal were based on IPCC guidelines. Estimates of emissions from coal combustion (CO_2, SO_2 and NO_X) were based on emission factors and Zimbabwe coal chemistry. From the elemental analysis of the Zimbabwe steam coal, the percentage of carbon and sulphur is known. From stoichiometry, 12 kg of carbon requires 32 kg of oxygen to form 44 kg of carbon dioxide or 1 kg of carbon produces 3.67 kg of carbon dioxide when it burns. 32 kg of sulphur requires 32 kg of oxygen to form 64 kg of sulphur dioxide or 1 kg of sulphur produces 2 kg of SO_2 when burnt. Therefore

$$CO_2 \text{ emitted per year} = \text{Total carbon in coal} \times 3.67 = \text{coal consumed per year} \times (\%\ C) \times 3.67 \tag{3.8}$$

SO_2 emitted per year = Total sulphur in coal ×2= coal consumed per year × (% S) ×2 (3.9)

[185] reports a coal NO_x emission factor of 3.4 kg NO_2/ton. Coal nitrogen content is generally not a good predictor of NOx emissions hence the choice of a NO_x emission factor. A simple correlation between coal nitrogen content and NO_x emissions has not been found despite the extensive research in this area [186]. Methane emissions and Global Warming Potential (GWP) were based on IPCC guidelines [140, 187].

Emissions (Gg CH_4) = Emissions Factor (m^3 CH_4/tonne) ×Tonnes of Coal Produced × Conversion Factor (Gg/ 10^6 m^3) (3.10)

where the conversion factor is given as 0.67 Gg/10^6 m^3

The emission factor for fugitive methane from underground coal mining at Hwange in Zimbabwe was reported to be 4.3 - 10m^3 CH_4/Mg of coal [175, 188]. A midrange value of 7.3 m^3 CH_4/Mg was assumed in this study. The Global Warming Potential (GWP) of greenhouse gases was based on the findings of the IPCC's Fourth Assessment report wherein the recommended GWP values of CO_2 and CH_4 are 1 and 25 [187] respectively. Our model assumes the milling of ZMSWH pellets and the firing of the mill product through the existing pipework and burners at Zimbabwe's coal-fired power stations as shown in **Fig 3.1**. The coal used is transported by conveyor belts to boiler bunkers for storage. From the bunkers, the coal is fed into volumetric feeders, which supply the coal mills (pulverizing mill). A more detailed description of the process is given by [189].

3.1.7 Emissions related to ZMSW, ZMSWH and coal transportation

Emissions factors were used to estimate the impact of transporting ZMSW, ZMSWH and coal for power generation. Nearly 29.7% of the total urban population resides in Harare [133]. This city with 1,501,363 dwellers is served by 47 refuse compactors. However, about 60 refuse compactors would be ideal [45]. Based on the Harare assessment, the rest of the urban population of 3,550,184 people would ideally require about 142 refuse compactors to give a grand total of about 202 compactors for the whole system as it exists now. The desired number of refuse compactors for 16 urban councils (including Harare and Bulawayo) was found to be about 104 [38]. An estimate of 202 trucks is reasonable for 32 locations. In order to estimate the emissions from the collection of waste, data on **Table 3.8** was used. In our model, ZMSWH would be transported by rail. Emission rates for carbon dioxide and methane were not locomotive-specific, but were based on fuel properties. They are largely independent of engine parameters and are primarily dependent on fuel properties hence the choice of using emission for diesel fuel.

3.2 Results and Discussion

3.2.1 Quantity and Characteristics of ZMSW

From **Fig. 3.3**, MSW generation rate for low-income nations might be predicted from the equation y=0.0004(GDP/capita) + 0.32. Our estimate for ZMSW generation rate is 0.64 kg/capita/day. As data from developing countries is generally unreliable, data would not be expected to fit well into this model hence a low R^2 value. Our estimate was averaged together with reported values (**Table 3.1**) to allow for a better estimation of the generation rate. The average value of ZMSW generation rate is 0.54 ± 0.14 kg/capita/day. For the current urban population this equates to 1,051.7 ± 270.7 Gg/yr from which 784. 2 ± 201.9 Gg/yr is collected. According to one investigation, 860.0 Gg/yr of ZMSW are produced and 705. 2 Gg/yr collected [102]. Another investigation by [52] reveals that 989. 0 Gg/yr are generated and according to a 2014 study by [45], Harare City council estimates that around 920.0 Gg/yr of household and industrial waste is produced in the capital. [48] asserts that about 2,500.0 Gg/yr of solid waste (industrial and household) are generated. There is considerable variation in the waste generation estimates largely due to the fact that specific data on ZMSW characteristics is not available from local authorities. **Table 3.9** is a statistical summary of ZMSW composition. Hoornweg and Bhada-Tata [134] compare waste composition by national income level. Despite being classified as a low-income nation, Zimbabwe’s MSW composition fits the profile of an upper middle-income nation. The quantity of paper (18.8±3.2 %) and plastics (16.1±3.5%) found in the waste stream is unusually high for a low-income nation. The relatively low organic fraction (32.9±6.6%) is not atypical of a low-income nation.

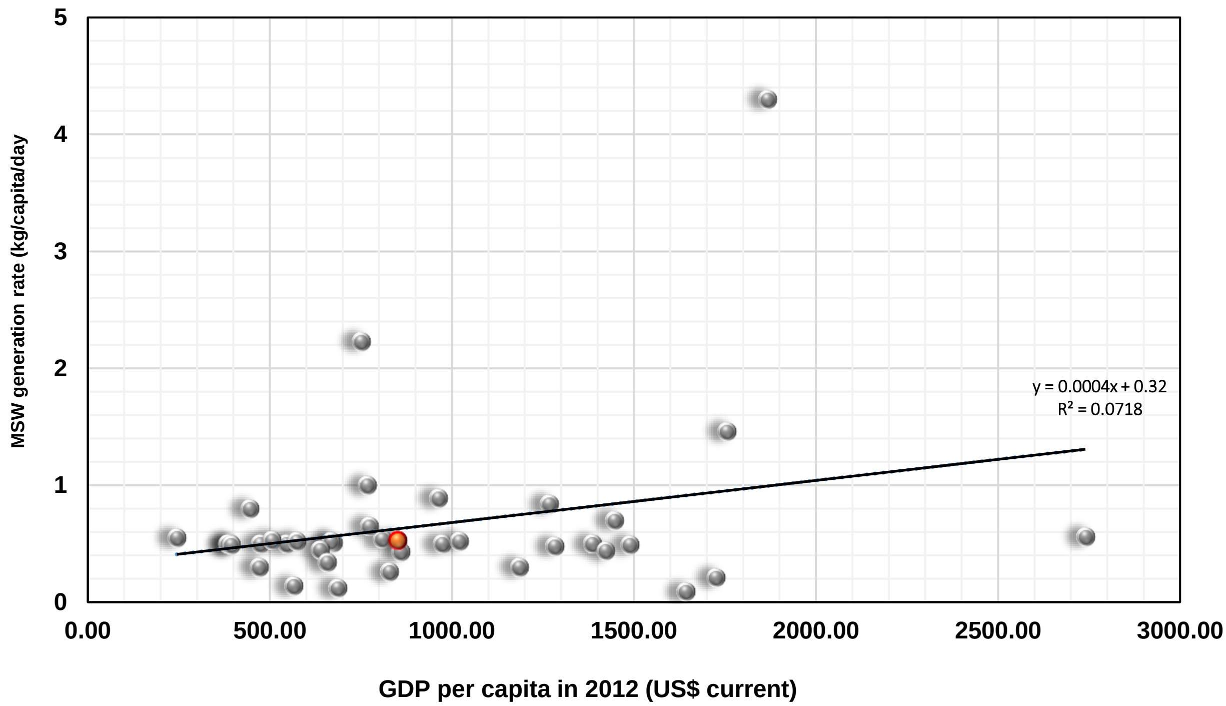


Fig. 3.3. MSW generation and GDP (both per capita) of 38 low-income countries MSW generation rates reported by [134] and GDP data from [133]. Red dot represents Zimbabwe (generation rate in 2012).

The high standard deviation in each waste category mirrors the large amount of variation in waste composition within the different urban areas of Zimbabwe. On a dry weight basis, 556.4 Gg/yr of ZMSW can be collected annually. In order to validate our model, we compared our simulated proximate and ultimate composition results with measured data as shown in **Table 3.10**.

Table 3.9 Statistical Analysis of ZMSW composition

Statistical Analysis	Paper & Cardboard	Glass & Ceramics	Metals	Plastics	Leather & Rubber	Textiles	Yard Waste & Sweepings	Wood	Putrescibles	Miscellaneous
Mean	18.8	4.0	6.5	16.1	1.9	3.8	4.4	4.1	32.9	7.5
Standard Error	1.6	0.5	1.4	1.7	0.5	0.7	1.2	0.8	3.3	1.4
Median	17.1	4.0	4.0	12.1	0.4	2.6	1.5	0.7	28.0	7.0
Mode	30.0	5.0	3.0	10.0	0.0	0.0	0.0	0.0	15.0	5.0
Standard Deviation	9.5	2.8	8.2	10.4	2.7	3.6	7.1	5.0	19.6	8.4
Sample Variance	89.5	7.9	67.4	107.3	7.1	12.7	50.4	24.7	385.2	70.1
Kurtosis	(1.2)	2.8	8.5	0.2	1.4	0.1	6.9	(0.5)	(0.5)	0.9
Skewness	0.2	1.2	2.8	0.9	1.5	1.0	2.4	0.8	0.6	1.0
Range	31.7	13.3	39.6	39.0	9.3	12.0	33.3	17.0	70.9	35.0
Minimum	3.3	0.0	0.0	3.0	0.0	0.0	0.0	0.0	5.0	0.0
Maximum	35.0	13.3	39.6	42.0	9.3	12.0	33.3	17.0	75.9	35.0
Confidence Level (95.0%)	3.2	1.0	2.8	3.5	1.1	1.4	2.4	1.7	6.6	2.8

With a few notable exceptions there is reasonable agreement between our simulation and real-life data. Using typical heating values of MSW components, the calorific value of ZMSW is 15.1 MJ/kg (dry basis). However, from the elemental content of ZMSW (**Table 3.10**), the Modified Dulong formula predicts a higher heating value of 19.9 MJ/kg. The two estimations from separate methods are within a percentage difference of 27 % between each other implying that the estimation here is reliable.

Table 3.10 Proximate and ultimate analysis of ZMSW as compared to measured values from different cities in Zimbabwe

City/Town	Proximate				Ultimate					
	Ash	VM	FC	MC	C	H	N	Cl	S	O
Harare*	12.5	79.2	8.4	30.9	47.1	5.1	1.6	0.7	0.8	30.9
Chitungwiza*	8.3	82.9	8.8	36.0	44.6	4.8	2.5	0.6	0.8	37.3
Epworth*	8.6	84.0	7.4	34.4	47.9	4.9	2.5	0.4	0.8	30.8
Average (field study)	**9.8**	**82.0**	**8.2**	**33.8**	**46.5**	**4.9**	**2.2**	**0.6**	**0.8**	**33.0**
ZMSW (our study)	20.4	68.2	9.9	29.0	45.9	6.1	1.6	1.6	0.2	24.2
Percentage difference	**70.2**	**18.5**	**19.8**	**16.7**	**1.5**	**21.8**	**31.6**	**85.7**	**120.0**	**30.4**

Field study conducted by *[145]

Table 3.11 Energy content analysis of ZMSW and ZOFMSW compared with field results

		Combustible fraction		Full MSW stream	
		Dry Basis	Wet Basis	Dry Basis	Wet Basis
*Field study**	Harare	22.26	14.62		12.87
	Chitungwiza	18.09	10.70		8.34
	Epworth	21.03	12.96		9.07
	Average	**20.46**	**12.76**		**10.09**
Our study	ZMSW	20.03	13.10	15.15	10.75
	ZMSW (using Dulong Formula)			19.92	
	ZOFMSW	18.39	12.22		
	ZOFMSW (using Dulong Formula)	23.69			

[145]

From **Table 3.11** we can see that our predictions measure up well against real data. From the characterization investigation, ZMSW could potentially provide about 8.52 million GJ of energy equivalent to the energy from about 320. 0 Gg of Zimbabwe steam coal. Our results concur with the estimates given by [52] of 8.9 million GJ being potentially recoverable from ZMSW. [102] contrasts our findings by suggesting that only 2.86 million GJ is recoverable. Plastics are expected to be the largest contributor in terms of energy at 3.8 million GJ due to their high calorific value. Paper and cardboard have the potential to contribute about 2.3 million GJ. The methane potential (MP) of ZMSW using the IPCC default methodology was calculated to be 62.2 Gg/year or 92.7 million Nm^3 per year. This is a specific methane generation rate of about 59.1 kg CH_4 per ton of MSW. [52] reports a value of 88.0 million Nm^3 per year.

3.2.2 Quantity and characteristics of ZOFMSW and ZMSWH

We estimate that 386.9 Mg/yr of ZOFMSW can be recovered (nearly 70% of ZMSW) on a dry basis, and is available for conversion into ZMSWH. **Table 3.11** compares the calorific value of ZOFMSW with reported measurements. Generally, our results are in good agreement with real world values. The predicted elemental composition of ZOFMSW is shown in **Fig. 3.4.**

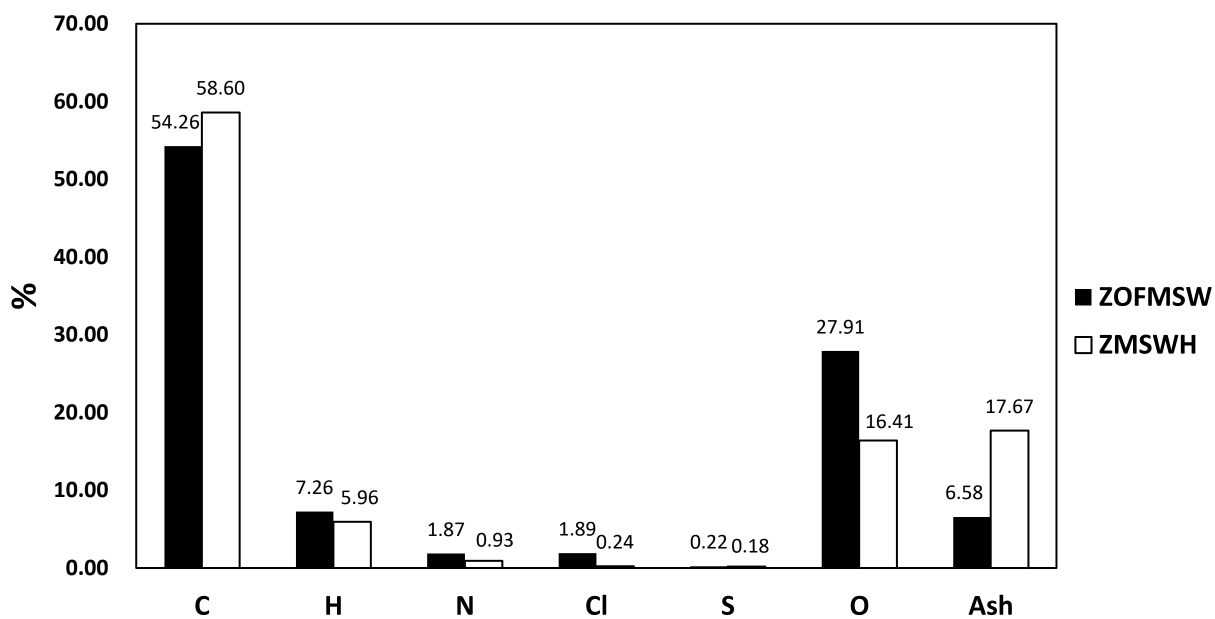


Fig. 3.4. Percent elemental composition of ZOFMSW and ZMSWH

We predict an ash content of 6.6%, volatile matter content of 81.1% and fixed carbon content of 12.3%. From the regression tree models and equation 6 and 7, the average value for the expected yield of ZMSWH from ZOFMSW is 75%. On a complete dry basis, a yield of about 289.3 Gg/yr of ZMSWH can be expected. From ZMSW to ZMSWH the overall yield is about 37%. From the regression tree model associated with hydrochar energy content, a caloric value of 22.47 MJ/kg is expected for ZMSWH. From the Dulong Formula, an energy content of 25.34 MJ/kg is expected. Oxygen and hydrogen content reduction from ZOFMSW to ZMSWH are expected as dehydration and decarboxylation occur during HTC with the removal of hydroxyl, carboxyl and carbonyl groups. The feedstock (ZOFMSW) presented very high H/C and O/C atomic ratios, which were 1.59 and 0.39. The H/C and O/C atomic ratios were expected to decrease to 1.22 and 0.21 after HTC treatment.

3.2.3 Environmental impact of co-burning MSW derived hydrochar for power generation

3.2.3.1 Environmental Impact of coal-fired power generation

Zimbabwe's thermal power generation is fickle hence a distinction between installed (assumes more efficient operations) and dependable capacity (existing situation) showed a wide variation. Hypothetically, if the plants had less breakdowns, the total coal consumption for thermal power generation would be about 4,700 Gg/yr. Hwange power station as the biggest station is expected to consume greater quantities of coal at 2,900 – 3,400 Gg/yr depending on the operating regime. Our own estimations reveal a total of 3,190 Gg/yr is consumed as the system exists now. There is reasonable agreement with reported value of 3,290 Gg/yr. Harare and Bulawayo stations require 700 Mg a day, Munyati demands 624 Mg a day whilst Hwange consumes 8,000 Mg a day or about 180,000 Mg per month and requires a stockpile of 30, 000 Mg according to newspaper reports [190, 191]. With an average calorific value of 25.5 MJ/kg, this represents about 120.1 million GJ and 81.5 million GJ input for installed and dependable capacity respectively.

The environmental impact of coal transportation is expected to be significantly lower relative to mining and combustion of coal. Significant CH_4 emissions stem mainly from coal mining operations. About 15.6 – 23.1 Gg/yr of CH_4 can be emitted from this source.

CO_2 and NO_X emissions from coal transportation stand at about 0.1 – 0.4 Gg/yr of NO_X and about 7.0 – 23.0 Gg/yr of CO_2. Total annual CO_2 emissions and combined GWP (from mining, transport and combustion) stand at approximately 8,700 Gg/yr and 9,060 Gg/yr CO_2e respectively for dependable capacity. Under installed capacity, total annual CO_2 emissions and combined GWP are 12,800 Gg/yr and 13,400 Gg/yr CO_{2e} respectively. This is depicted in **Fig. 3.5**. SO_2 emissions stand at about 154 -228 Gg/yr with a significant proportion attributed to coal combustion.

Table 3.12 Estimated ZMSW generation by city/town

Urban Area	ZMSW Generation (Gg/yr)	Urban Area	ZMSW Generation (Gg/yr)
Harare	381.46 ± 52.33	**Beitbridge**	10.82 ± 1.48
Bulawayo	167.80 ± 23.02	**Redcliff**	9.23 ± 1.27
Chitungwiza	91.65 ± 12.57	**Victoria Falls**	8.67 ± 1.19
Mutare	48.19 ± 6.61	**Rusape**	7.79 ± 1.07
Epworth	43.01 ± 5.90	**Chiredzi**	7.82 ± 1.07
Gweru	40.55 ± 5.56	**Kariba**	6.79 ± 0.93
Kwekwe	25.92 ± 3.55	**Karoi**	7.35 ± 1.01
Kadoma	23.75 ± 3.26	**Chipinge**	6.50 ± 0.89
Masvingo	22.57 ± 3.10	**Gokwe**	6.18 ± 0.85
Chinhoyi	20.02 ± 2.75	**Shurugwi**	5.63 ± 0.77
Norton	17.36 ± 2.38	**Gwanda**	5.20 ± 0.71
Marondera	15.92 ± 2.18	**Hwange**	9.64 ± 1.32
Ruwa	14.56 ± 2.00	**Chivhu**	3.33 ± 0.46
Chegutu	12.99 ± 1.78	**Plumtree**	2.99 ± 0.41
Zvishavane	11.62 ± 1.59	**Mvurwi**	2.71 ± 0.37
Bindura	11.22 ± 1.54	**Banket**	2.53 ± 0.35

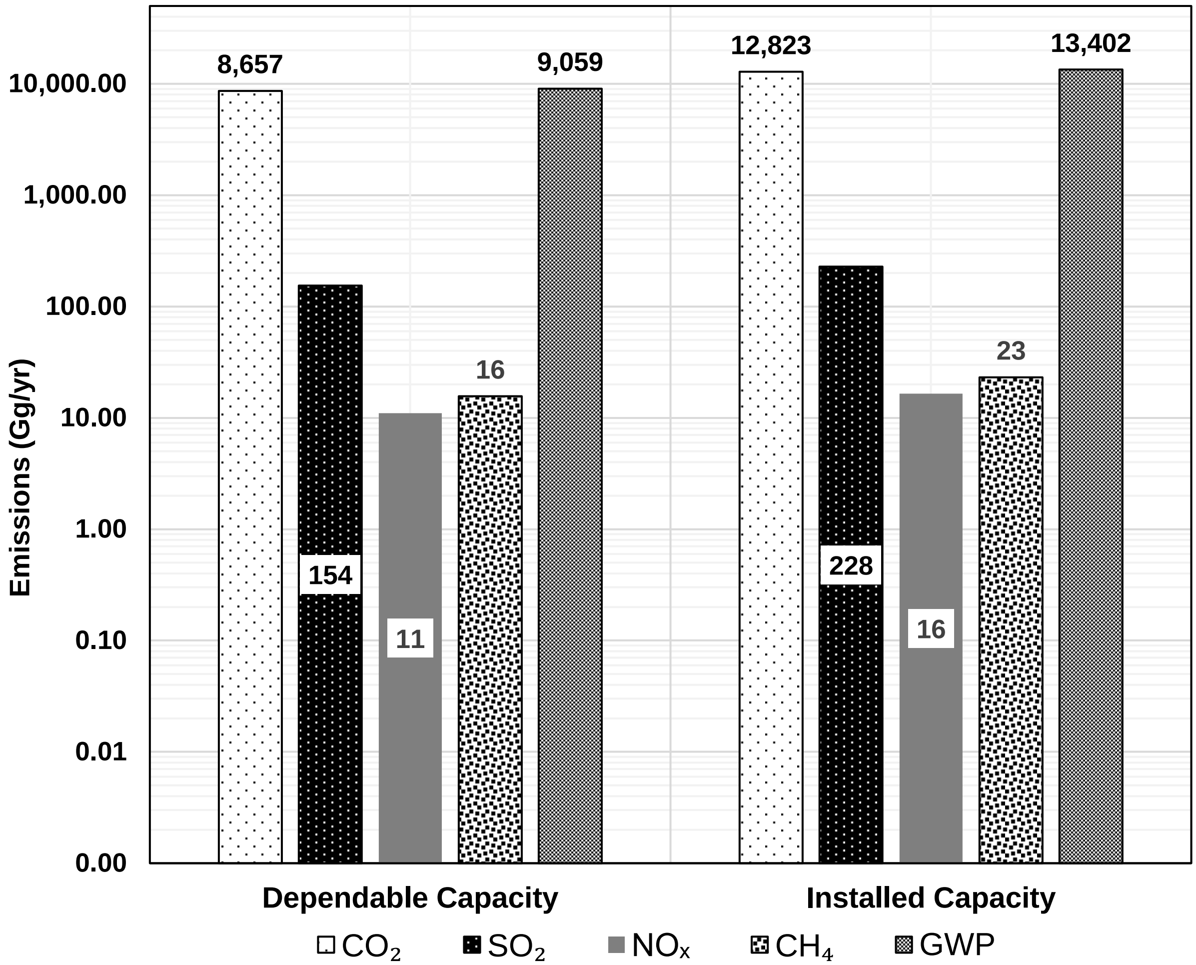


Fig. 3.5. Total emissions related to coal mining, transport and combustion for power generation

3.2.3.2 Environmental Impact estimate of HTC

The estimated fuel used to collect waste is about 8.8 million L/yr. The most significant amount of emissions related to refuse collection are CO_2 at 7.3 Gg/yr. **Fig. 3.4**. is a prediction of the elemental composition of hydrochar. A reduction in chlorine and sulphur content is expected due to dechlorination and desulphurization properties of HTC. Chlorine mainly from PVC (organic chlorine) and salt (inorganic chlorine) is converted into HCl and discharged with steam during hydrothermal carbonization resulting in a product with reduced Cl content compared to the original MSW. Sulphur and nitrogen are expected to follow a similar trait whereby S and N partly remains in the ZMSWH as it is released into the gas and liquid phase during hydrothermal treatment. Total SO_2, NO_X,

CH_4, CO_2 emissions and GWP are shown in **Fig. 3.6**. NOx emissions are expected to originate mainly from combustion. ZMSWH contains about 2.7 Gg of nitrogen based on the elemental composition. The contributors of nitrogen are proteins in food wastes and textiles. These sources of nitrogen comprise of chemically-bound nitrogen in organic form e.g. amines and inorganic nitrogen compounds and upon combustion, N_2 or NO is formed. Therefore, the amount of fuel-NO emitted depends on the ZMSWH quantity combusted. CH_4 quantities are expected to be very low as the source will mainly be from vehicles involved in ZMSW collection and transportation

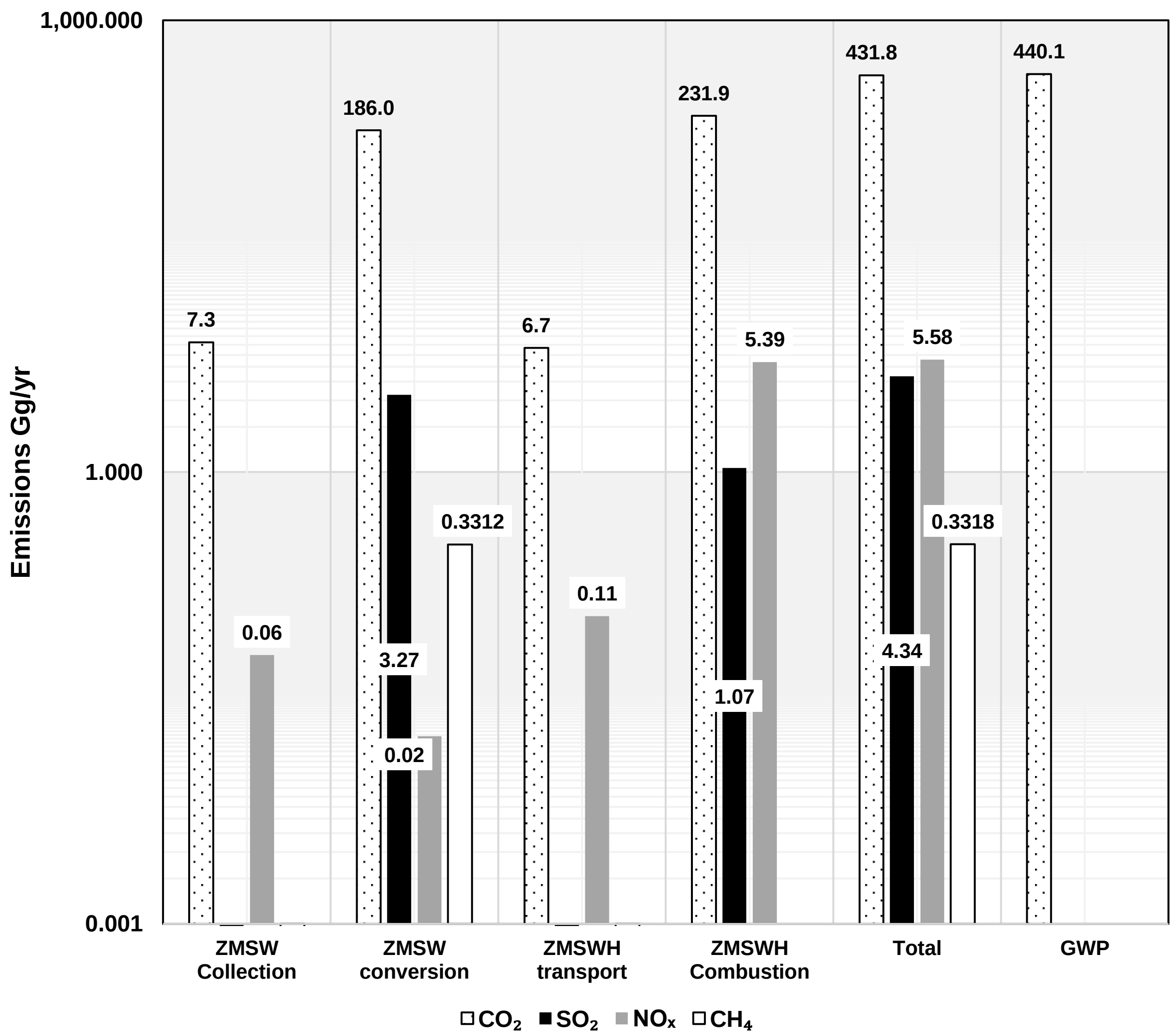


Fig. 3.6. Emissions related to ZMSWH formation, transport and combustion

. Projected total CO_2 emissions are the region of 431.8 Gg/yr. In terms of sources of CO_2 emissions, our model predicts that the proportion of fossil carbon (e.g. carbon from plastics) is about 37% and the proportion of biogenic carbon is 63% in ZOFMSW. A maximum of 231.9 Gg/yr CO_2 is expected from the direct combustion of the hydrochar. Estimates of the net emissions from the co-burning of ZMSWH and coal will be given under different scenarios in the following section

3.2.3.3 Environmental impact of co-combustion under different scenarios

Due to the uneven distribution of the urban population (MSW source) relative to the size and location of coal-fired stations as shown in **Fig. 3.2**, MSW transportation and logistics challenges may adversely affect the viability of the proposed technology. For example, roughly 66 % of Zimbabwe's urban population is near Harare power station with a nameplate capacity of 120 MW and less than 2 % of the urban population is near Hwange power station with an installed capacity of 980 MW. Hence it would be necessary to transfer excess alternate fuel from Harare to Hwange. **Table 3.12** gives an estimate of the quantities of MSW generated in each urban city based on national generation rate and relative urban population size. This formed the basis of estimation of emissions under different scenarios. The aims of the scenario analysis are:

- identify possible pathways to attain the goal of co-firing of ZMSWH in Zimbabwe's power stations
- to identify the maximum possible blend ratio for each route
- evaluate the environmental impact of each route relative to current emissions (baseline)

Under all scenarios, MSW would still be collected, however conversion to hydrochar and subsequent co-burning in power stations would depend on the scenario. The scenarios that shall be considered in this section are:

Scenario 1: Collection of ZMSW from all urban areas and entire conversion to ZMSWH

Scenario 2: Collection of ZMSW from all urban areas but conversion to ZMSWH limited only to waste collected from major cities (remaining ZMSW is landfilled)
Scenario 3: Collection of ZMSW from all urban areas and conversion to ZMSWH limited only to waste collected from cities in relatively close proximity to coal-fired power plants (the rest is landfilled)
Scenario 4: Collection of ZMSW from all urban areas and conversion to ZMSWH limited to waste from close cities. ZMSWH requirement is determined by power plant capacity
Scenario 5: Collection of ZMSW from all urban areas and conversion to ZMSWH limited to waste from Harare.

The term ‘Close proximity’ for scenario 3 or ‘close cities’ for scenario 4 refers to cities within a 50km range. There are 32 cities/urban councils in Zimbabwe with 10 being classified as major (in terms of population size). The largest is Harare followed by Bulawayo. For scenario 3 and 4, the following cities meet the specifications:

Harare to Harare Power Station – 4km
Bulawayo to Bulawayo Power Station - 2.3 km
Kwekwe to Munyati Power Station -35 km
Kadoma to Munyati Power Station -50 km
Hwange to Hwange Power station – 6 km

The difference between scenario 3 and 4 is that in scenario 3 waste is that waste conversion occurs in the cities near stations and hydrochar is not transported to other cities. In scenario 4 excess hydrochar is transported to Hwange power station with the largest capacity. The 10 major cities are Harare, Chitungwiza, Mutare, Epworth, Chinhoyi, Bulawayo, Gweru, Masvingo, Kwekwe and Kadoma (Scenario 2).

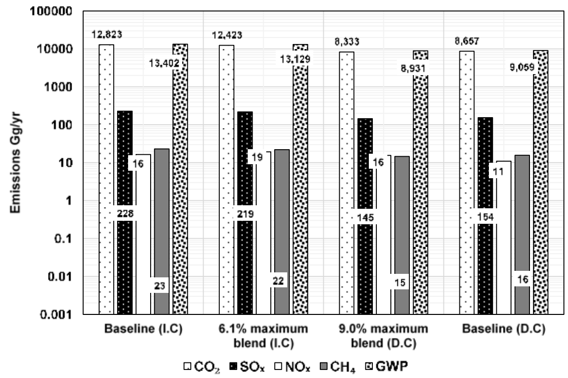


Fig. 3.7a. Projections for total direct emissions under scenario 1

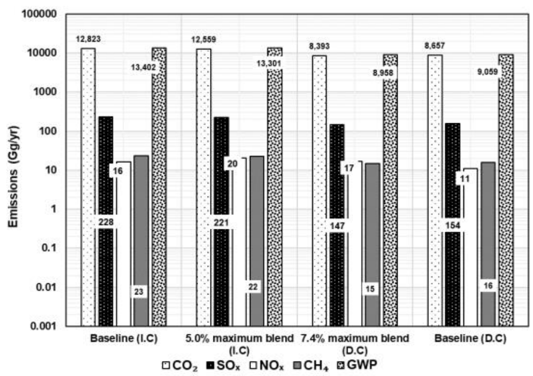


Fig. 3.7b. Projections for total direct emissions under scenario 2

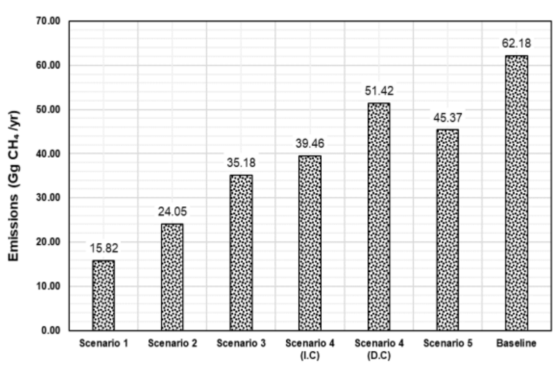


Fig. 3.7f Methane potential of unconverted ZMSW under different scenarios

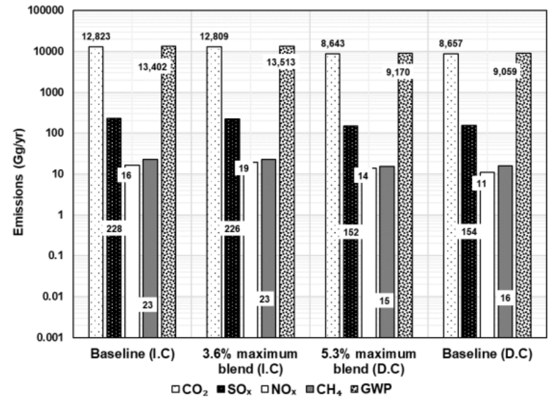


Fig. 3.7c Projections for total direct emissions under scenario 3

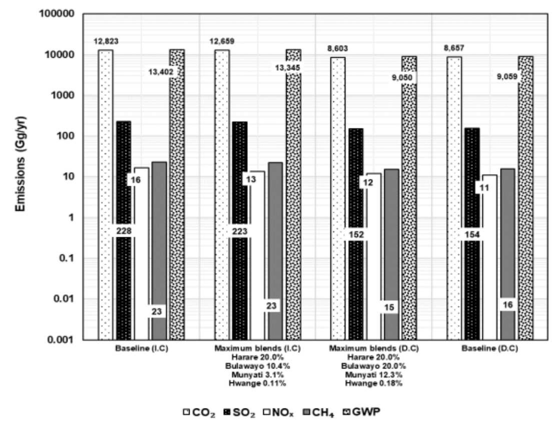


Fig. 3.7d. Projected total emissions under scenario 4

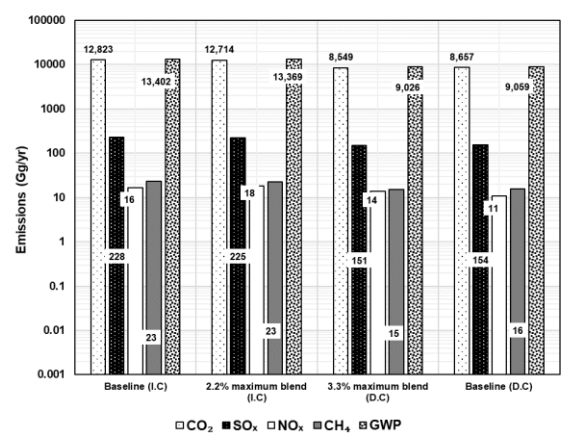


Fig. 3.7e. Projected total emissions under scenario 5

Fig. 3.7 a-e, shows projections for all scenarios. In scenario 1, ZMSW is collected from all urban centres, converted to hydrochar and then distributed to each coal-fired plant according to its capacity. 289.3 Gg/yr of ZMSWH is available for distribution to all thermal power plants. The maximum blend ratios are 9.0% and 6.1 % for dependable capacity (D.C) and installed capacity (I.C) operations. Compared to the emissions from the existing situation (baseline), Fig 3.7a, under this scenario, GWP drops from 13.4 to 13.1 million for I.C and 9.1 to 8.9 million CO2e for D.C. This is only a slight reduction of 2.2 % for both I.C and D.C respectively. CO2 emissions would decrease slightly by 3.1% and 3.7 % for I.C and D.C respectively. NOx emissions are expected to rise under this scenario (18.8% for I.C and 45.5 % for D.C). To counteract the rise in NOx emissions we recommend the installation of air pollution control devices (APCDs), in particular, selective catalytic reduction (SCR) units, which can reportedly decrease NO_x emissions (Ma et al., 2016). Overall SO_x emissions are expected to decline from 228.1 Gg/yr to 218.6 Gg/yr (a 4.2% decline) for I.C and from 154.1 to 145.0 Gg/yr (5.9% reduction) for D.C per year. Methane will decrease by 4.5% and 6.6% for I.C and D.C respectively. **Fig. 3.7e** shows the methane potential of the remaining uncollected waste. The conversion of all collected ZMSW will reduce the methane potential of household waste from 62.2 to 15.8 Gg CH_4/yr.

Under scenario 2, **Fig 3.7b**, ZMSW is collected from 10 major cities and a yield of 237.9 Gg/yr of ZMSWH is expected. The alternate fuel is distributed to each station according to capacity. A maximum blend of 5.0% and 7.4 % for IC and DC is possible in this scenario. Under scenario 3, ZMSW from 6 urban areas (Harare, Bulawayo, Kwekwe, Kadoma, Victoria Falls and Hwange) is converted to yield about 168.4 Gg/yr of ZMSWH. This fuel is hauled to each station according to the capacity of each respective plant. To use up all the fuel, a maximum blend of 3.6% and 5.3% is possible for I.C and D.C respectively as shown in **Fig 3.7c**. Under scenario 4, **Fig 3.7d**, waste is collected from 6 cities near power stations but in this case (like Scenario 3), however, the quantity of ZMSW converted depends on the quantities the city/town can provide. Harare can potentially provide about 104.9 Gg/yr of ZMSWH meaning Harare power station can theoretically accept a blend ratio beyond 20% for either I.C or D.C. Hwange power station, however, is situated next to towns that can provide a maximum of 3.7 Gg/yr of ZMSWH.

Under scenario 5, ZMSW from Harare is converted to yield about 104.9 Gg/yr of ZMSWH. This fuel is hauled to each station according to the capacity of each respective plant. To use up all the fuel, a maximum blend of 2.2% and 3.3% is possible for I.C and D.C respectively as shown in **Fig 3.7e**.

In all scenarios, SO_X emissions are expected to be reduced. Greater NO_X emissions have to be expected when burning ZMSWH. The partial substitution of coal using ZMSWH (6.1 to 9.0% of total coal consumption) is not enough to offset the NO_X emissions emanating from ZMSWH combustion. Although our model predicts increases in NO_X emissions it must be understood that this may not be so in practice. Despite the expected decrease of NOx with increase in biomass proportion, pilot- and full-scale testing showed mixed results according to [192]. Overall, in either one of these scenarios, the greenhouse emissions rates relative to the baseline are expected to be more or less the same. The most suitable route for Zimbabwe from an environmental perspective would be the one with relatively significant reductions in methane potential. Using this reasoning, Scenario 1 is the likely candidate, as it can potentially result in less impact on the environment. This route would likely be the most expensive and not economically viable. However, this is conjecture at this point, without an economic feasibility study we cannot draw conclusions on the actual economic viability. The financial viability of each route would have to be carefully examined in order to draw up conclusions on the optimally balanced scenario (environmentally friendly and economically efficient).

3.3 Conclusion

Environmental issues raise questions about the application of HTC in developing countries. This study set to determine life cycle emissions from MSW-derived hydrochar co-combustion in Zimbabwe's coal power stations. Five scenarios differing in the amount of MSW converted based on the spatial distribution of MSW and stations were developed to assess the environmental impact of the technology. Results confirm that greenhouse gas emissions from unsanitary MSW landfills and coal-fired power plants can be abated by HTC. Roughly 1,051.7 ± 270.7 Gg/yr of MSW are generated and a yield of 289.3 Gg/yr of hydrochar is possible. This can substitute between 6.1 – 9.0 % of coal used in thermal power plants with coal consumptions rates of 3,200 – 4,700 Gg/yr. Under the best scenario, slight reductions in overall direct emissions from the co-burning route; 4.2% for SO_X, 4.5 % for CH_4, 3.1% for CO_2, 2.2 % in Global Warming Potential (GWP) and a 18.0 % rise for NO_X can be expected. The diversion of MSW from landfills can significantly reduce the methane potential of household waste from 62.2 to 15.8 Gg CH_4/yr under this scenario. Financial and technical resources for developing hydrothermal carbonization technology are essential for Zimbabwe's future. It is recommended that future research efforts focus on the economic evaluation of the process in developing nations. From the foregoing study, it would be necessary for relevant authorities to take immediate action by adopting the technology to prevent additional irrecoverable damage to the environment. The financial viability of each route would have to be carefully examined in order to draw up conclusions on the optimally balanced scenario (environmentally friendly and economically efficient)

Chapter 4: Stochastic economic analysis of coal-alternative fuel production from MSW

The economic feasibility of a nation-wide HTC based solid waste management system is explored in this chapter. Assessment of this system is based on a stochastic 20-year discount cash model and modification of the percentage of delivered equipment cost method. The main economic indicators of economic viability are NPV, IRR, Payback Period, Profitability Index and an estimation of the contingency reserves required.

4.0 Early-stage capital cost estimation of process plants

Performing capital cost estimations for new technologies is a difficult task, especially for HTC where information and experience on an industrial scale is limited. Early-stage capital cost estimations fall into three categories. From an exponent estimate, the capital cost of a new plant is deduced using data from operational plants by taking the ratio of capacities and raising by an exponent. Factorial estimates use factors to multiply certain plant costs to produce a cost estimate for the overall plant. Thirdly, functional unit estimates make use of the values of the fundamental process parameters known in the initial stages of process development to predict the capital cost of the corresponding plant [279]. The accuracy of the capacity exponent method is rather low given that detailed flow-sheeting or an equipment list is unnecessary [280, 281]. Underestimation of capital costs is caused by an incomplete listing of all the equipment needed in the process [282]. It is not ideal for new processes as it requires information available about the capacity and investment of a similar plant [283]. The best accuracy obtainable from the exponent method is ±40% [279, 284].

Introduced by [285], factorial estimates have been improved and modified by various authors over the years [286-294]. Most capital cost estimates are based on the factorial method, more specifically, on the estimate of the purchase cost of the major equipment items making up the process, the other costs being estimated as factors of the equipment cost [295]. Early work on the functional unit method began with [296-301] who collected historical plant data and attempted correlations. A functional unit, the premise for the method, includes all equipment and ancillaries necessary for the operation of a unit or significant step in a process. The total capital cost is summed up from all functional units. These methods are derived by statistical analysis of historical plant data and are typically expressed by a combination of equations, charts, tables and plant classifications [279]. Tsagkari et al [302] report that [279, 286] were the last to propose this method. Factorial estimations are accurate up to 10% - 30% at best [280].

The aforementioned estimations are conventionally based on deterministic models which are relatively simple to build and run because they quantify the impact of a single changed variable on the model's result at an instant. A sensitivity analyses cannot fully overcome the shortcomings of such models because they too can only quantify the impact of a single variable change at a time. This makes these models insensitive to uncertainty or risk. Akbari et al [59] iterates that previous HTC techno-economic studies are not detailed enough for an HTC plant. A stochastic framework, however, considers the simultaneous change in several variables to quantify the impact on the economic assessment result [303]. The cost estimation for commercial HTC plants is inherently stochastic and needs statistical approaches that consider the uncertainty of many input variables in order to produce estimates with quantifiable uncertainties. As shown in **Table 4.2**, certain cost variables are expressed as a range meaning that a deterministic model would not fully capture the uncertainties in costs. Uncertainty analysis of cost data can be achieved either by bootstrapping (as a regression method) when historical data of a similar plant is available or Monte Carlo simulations when cost data are unavailable [283]. Introducing a stochastic approach further provides a quantification of the optimum contingency reserves required for the inclusion of risks [304].

The objective of the present study is to develop a stochastic cost estimation approach for the construction and operation of an HTC based WTE plant by modifying the percentage of delivered-equipment cost method. Instead of using either multiplication factors or percentages as in the conventional method, probability models will be introduced to improve the quality of the estimates. The paper will also present a way of calculating and reporting contingency reserves required instead of using the deterministic rule of thumb approach. Traditionally contingency is applied by means of a percentage addition to the base estimate, a minimum 10% contingency is commonly used. Higher percentages of up to 50% for new processes are recommended [305]. However, this method is fundamentally flawed. A 10% or 50% contingency does not necessarily guarantee with 100% certainty that the total project cost will not exceed its estimated cost by 10% or 50%. It neither conveys how much confidence can be placed on that figure. To this end, a range estimate using a contingency-confidence profile is proposed in this study in light of the uncertainty surrounding cost estimations. As with common practice, economic viability will be assessed using the internal rate of return (IRR), net present value (NPV), return of investment (ROI) and payback period. Monte Carlo simulations will be used to assess the degree of uncertainty associated with these key economic indicators. The economic viability of the proposed MSW-HTC system in Zimbabwe will be considered under two scenarios; scenario 1 in which it is a public/government-run operation whereas scenario 2 assumes the private sector-handles the system. Parastatals, government ministries, companies wholly owned by the government and statutory corporations are exempt from corporate income tax [306]. As the effective corporate tax rate (shown in **Table 4.2**) might have a significant bearing on the profitability of the investment, these two scenarios were considered.

4.1 Materials and Methods

4.1.1 Basic steps of economic analysis and process description

The following procedure was adopted in the evaluation:1) Development of process flow diagram 2) Calculation of mass and energy flows 3) Sizing of major equipment 4) Estimation of the probabilistic capital cost 5) Estimation the probabilistic production cost 6) Estimation of revenue streams using probability models 7) Development of a stochastic discounted cash flow model to calculate the measures of profitability. Our approach is depicted in **Fig. 4.1**. A brief description of the process will be given here. The first stage in the proposed plant involves the conversion of Zimbabwe's MSW (ZMSW) to an organics fraction after the removal of metals, glass, ceramics, i.e. the incombustibles. ZOFMSW is a heavy fraction consisting of small-sized particles containing organics, plastics, wood, rubber, etc. ZFOMSW is conveyed to the hydrothermal carbonization reactor to be converted into ZMSWH (hydrochar). After drying, ZMSWH is pelletized and transported to the final user. The main stages of ZMSW processing in order of sequence are pre-inspection, bag ripping, metal separation, shredding, air classification, HTC, drying and pelletization. Specific details on the full nation-wide scale HTC system for Zimbabwe, ZMSW feedstock and ZMSWH properties, methodologies for modelling organic fraction of ZOFMSW yield can be found in a previous publication by [247]. Two of the largest urban cities, Harare and Bulawayo, were chosen for the locations of the plants. Several authors have mentioned that the major bottleneck to the success of bioenergy plants is biomass spatial distribution and transportation costs [307-311].

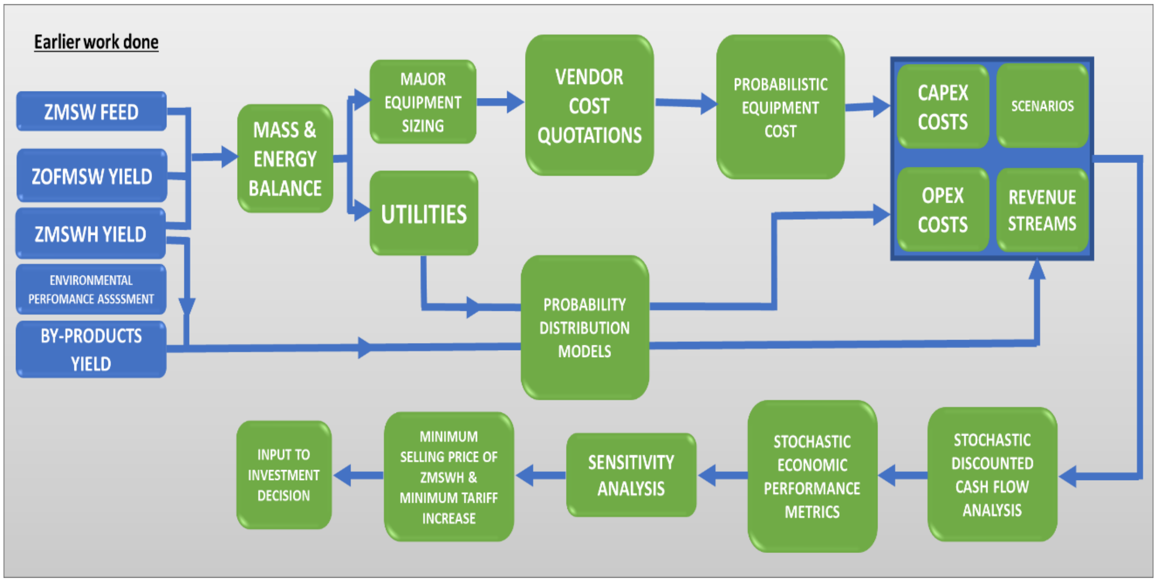


Fig. 4.1 Overview of economic analysis approach

Some reports indicate that transportation costs account for at least 20% and up to 76% of total system operation costs [66, 312, 313]. Since the collection and transportation of MSW feedstock could potentially impose constraints on the economic viability of the system, the plants are located closer to large population centers. Harare and Bulawayo in particular, are home to about 61% of Zimbabwe's urban population [314]. These cities are also industrial hubs [315] with power stations located there. Industry could potentially benefit from the locally available coal-alternative fuel. Details on the spatial distribution of ZMSW feedstock are given in a previous study by [247]. Secondly, economy-of-scales usually favor large infrequent HTC plants compared to small decentralized ones for a given wide coverage area despite the slight increase in feedstock cost due to longer transportation distances [244]. Lastly, specific investment costs can be expected to decrease with increasing plant capacity. For example, a plant with 5000 Mg capacity requires an investment cost of about €260 /Mg whereas for 80,000 tons capacity, €50 /Mg would be required [316, 317].

4.1.2 Mass and Energy Balance calculations for hydrothermal conversion of MSW

Mass and energy balances were calculated using pilot-scale data from [128] as shown in **Table 4.1**. Equations 6.1 to 8.1 [128, 318] were used in calculations to determine raw material and utility requirements. For the mass balance:

$$m_{ZOFMSW} + m_{steam} + m_{MC_{ZOFMSW}} = m_{ZMSWH} + m_{off-gas} \qquad (4.1)$$

where m_{ZOFMSW} = dry mass of ZOFMSW, $m_{MCZOFMSW}$ = mass of moisture content in ZOFMSW, m_{steam} = steam flow entering the reactor, m_{ZMSWH} = hydrochar mass, $m_{steam\ off-gas}$ = condensed steam mass from the reactor to the condenser

For the energy balance, the equations stated in words are:

$Energy\ from\ steam$ + $Energy\ from\ motor$ + $Energy\ from\ utility$ = $Energy\ for\ steam\ injection\ phase$ + $Energy\ for\ holding\ period$

(4.2)

$Energy\ from\ steam$ = $Energy\ from\ fuel$ − $Stack\ heat\ loss$

(4.3)

$Energy\ from\ steam\ injection\ phase$ = $Energy\ from\ steam\ at\ injection$ + $Energy\ from\ motor\ at\ injection$ + $Energy\ from\ utility\ at\ injection$ = $Energy\ to\ heat\ reactor$ + $Energy\ to\ heat\ MSW$ + $Energy\ to\ heat\ water$

(4.4)

$Energy\ for\ holding\ period\ phase$ = $Energy\ from\ steam\ at\ holding$ + $Energy\ from\ motor\ at\ holding$ + $Energy\ from$ utility $at\ holding$ = $Heat\ losses$

(4.5)

In mathematical notation it can be stated in this way:

$$\left(m_{water,i} + m_{water,h}\right)\left(h_{steam_{(T,P)}} - h_{water_{T_0}}\right) = \left[m_{fuel}C_{fuel}\right] - \{E_{LOSS}\} \qquad (4.6)$$

$$E_h = m_{water,h}\left(h_{steam_{(T,P)}} - h_{water_{T_0}}\right) + 208A_h + \left(\frac{m_{water_h}}{1000t_h}E\right) = U_{reactor}t_hA_{reactor}(T - T_0)$$

(4.7)

$$E_i = m_{water,i}\left(h_{steam_{(T,P)}} - h_{water_{T_0}}\right) + 208A_i + \left(\frac{m_{water_i}}{1000t_i}E\right)$$
$$= \left[m_{reactor}.c_{p_{reactor}}(T - T_0)\right] + \left[X \cdot m_{ZOFMSW}\left(h_{sat(T)} - h_{water(T_0)}\right)\right]$$
$$+ \left[m_{ZOFMSW}c_{p_{ZOFMSW}}(T - T_0)\right]$$

(4.8)

where $m_{water\ i,\ h}$ = accumulative water consumption in boiler at injection and holding phase respectively (kg) measured at boiler feed water inlet , $m_{reactor}$ = reactor mass (kg), $A_{i,h}$ = motor ampere during steam injection and holding phase respectively (A), $t_{i,\ h}$ = length of steam injection and holding phase respectively (s), E = boiler utility consumption, (kW), $cp_{reactor}$ = reactor specific heat capacity ($kJkg^{-1}K^{-1}$), cp_{ZOFMSW} = dry ZOFMSW specific heat capacity ($kJkg^{-1}K^{-1}$), X = moisture content, wet base (kg/kg), $h_{sat}(T)$ = enthalpy of water at saturated liquid temperature $kJkg^{-1}$), $h_{steam\ (T,P)}$ = enthalpy of steam at operational temperature and pressure ($kJkg^{-1}$), $h_{water\ (T0)}$ = enthalpy of water at initial temperature T_0($kJkg^{-1}$), $U_{reactor}$ = reactor overall heat transfer coefficient ($Wm^{-2}K^{-1}$), $A_{reactor}$ = surface area of reactor (m^2) and C_{fuel} = fuel heating value (kJ/kg)

The energy required for drying, Q_{drying}, is calculated using the equation given by [246]:

$$Q_{drying} = m_{ZMSWH}\int_{T_{IN}}^{T_{ZMSWH}} c_{p_{ZOFMSW}}dT + m_{MC_{ZMSWH}}\int_{T_{IN}}^{T_{ZMSWH}} c_{p_{ZOFMSW}}dT$$
$$+ m_{vapour}(H_{out} - h_{in})$$

(4.9)

where m_{ZMSWH} is the feed rate of ZMSWH, C_{pZMSWH} is the specific heat capacity of ZMSWH , T_{ZMSWH} is the temperature of the feed exiting the drum, T_{IN} is the temperature of wet ZMSWH, $m_{MC_{ZMSWH}}$ is the flow rate of water in the ZMSWH, m_{vapour} is the mass flow rate of steam evaporated from the ZMSWH, H_{out} is the enthalpy of steam at the exit of the drum and h_{in} is the enthalpy of water at T_{IN}. In our model T_{ZMSWH} and T_{IN} are assumed to be 105°C and 25 °C respectively. Low-temperature drying (at the operation temperature of 30-110 °C) is well developed and beneficial for reducing emissions and drying costs [319]. Assuming a 55% moisture content for ZMSWH immediately after exiting the reactor [128] and drying to 15% moisture content before pelletizing, the energy required for drying per kg of hydrochar is roughly 230.8 kJ. The optimum moisture content of pelletization is roughly 10–15% [320].

Table 4.1 Pilot scale data for HTC batch reactor processing MSW [128]

Parameter	*Value*	*Parameter*	*Value*
Pressure (MPa), P	2.3	Boiler Utility (kW), E	3.92
Temperature (°C), T	220	Stirrer motor ampere, A_h	53.51
Total processing Time (s), $t_i + t_h$	7800	Energy required per kg MSW, (MJ/kg)	1.90
Holding period (s), t_h	5400	Boiler fuel calorific value (MJ/kg), C_{fuel}	35
MSW in (kg), m_{MSW}	401.3	Reactor overall heat transfer coefficient (W/m2. K), $U_{reactor}$	715
Solid product out (kg), $m_{hydrochar}$	317.5	MSW Specific Heat Capacity (kJ/kg.K), cp_{MSW}	1.43
Solid material loss (kg)	83.8	Reactor surface area (m^2), $A_{reactor}$	14.5
Moisture in MSW in (kg), $m_{moisture}$	198.9	Reactor specific heat capacity (kJ/kg.K), $c_{p_{reactor}}$	0.456
Moisture in product out (kg)	402.5		
Total Boiler Water consumed (kg), $m_{water\,i} + m_{water\,h}$	607		
During Steam injection phase (kg) $m_{water\,i}$	396		
During Holding phase (kg) $m_{water\,h}$	211		
Off-gas/ condensed steam out (kg), $m_{off-gas}$	403.4		

4.2 Capital costs and profitability estimations using Monte Carlo simulations

The capital costs and profitability were calculated by using a modified form of the purchased equipment cost method [281] that uses percentages of delivered equipment. Confidence in this method is justified because the authors are considered authorities in cost estimations and are frequently quoted in other publications [280, 321-330]. The modifications were made on the accompanying Cost & Evaluation Workbook provided by [281]. Monte Carlo simulations were performed using Palisade's @RISK software [200] in line with the steps outlined by [288]. The number of iterations used for our model is 50,000. Instead of using deterministic or static values for the percentages of the different cost elements, these percentages were substituted with probability distributions (**Table 4.2**).

Table 4.2 Summary of analysis data and assumptions (major stochastic variables included)

Component	*Value and Description*
Total MSW feed supply (ZMSW)	784.2 Gg/year (wet basis), 556.4 Gg/year (dry basis), 386.9 Gg/year of ZOFMSW (organic fraction of ZMSW on a dry basis) [247]
Hydrochar yield (ZMSWH)	289.3 Gg/year (dry basis). [247] Moisture content is 6% when sold
ZOFMSW Density	0.295 kg/m^3 Using equation from [331] that relates the fraction of each component in ZOFMSW and the density of each component
Specific Heat capacity	1.4 kJ/kg/°C for ZMSW (Based on fraction of components and their respective capacities ([332])) 1.95 kJ/kg/°C for ZMSWH [333]
Harare plant	566.7 Gg/yr of ZMSW transferred to plant, 420.9 Gg/yr of ZOFMSW [247] (Based on relative urban population size and proximity)
Bulawayo plant	217.5 Gg/yr of ZMSW transferred to plant, 161.5 Gg/yr of ZOFMSW [247]
Mode of operation	24 hr/day for 330 day/yr in a batch mode
Time horizon of analysis	20 years (typical service life for WTE plants is up to 30 years [334, 335] prolongable to 40-50 years. Conventional time horizon for cost analysis is 20-25 years [336]
Interest rate on borrowed funds	9-12%
Discount Rate	8-20% (Discount rates are typically lower (3–7%) for developed nations. Add the risk premium to the current U.S 30-year treasury bond rate of 2.84% to estimate for developing nations [337]. Zimbabwe's risk premium is 15% to give a rate of 18%)
Tax rate	0% for government run operation

	0-26% for private sector-run operation (corporate tax is 25% and a 3% AIDS levy is imposed on the tax chargeable giving an effective cooperate tax rate of 25.75% in Zimbabwe [338]. No policy exists for the justification of a single point value hence a variable rate was assummed for the provate sector
Depreciation Method	Modified Accelerated Cost Recovery System (MACRS) schedule of 7 years
Tariff/MSW collection fee	$3.06 - $4.56/month.household (The mean tariff per property per month for 18 urban councils are US$3.06, US$4.19 and US$4.56 for high, medium and low-density suburbs [38]. Urban housing stock stood at 667,561 in 2009 [339] in Zimbabwe.
Income from selling scrap metal	US$68-US$384/Mg LME scrap steel peaked at US$384/Mg for the period January 2018 to May 2019 [340] whilst it fetches US$68/Mg in South Africa [341]. ZMSW has metal composition of 6.5%. Roughly 49.4 Gg/yr of metal is present in ZMSW and about 90% of it is available for sale after separation to form ZOFMSW.
ZMSWH Selling Price	US$35-59/Mg (As this will be a competitor and new product, price was kept below that of coal. The price of coal is US$59-65/Mg [342]
Electricity tariff	0.09- 0.14 US$/kWh [343]
Electricity consumption	4.7 to 7.8kWh per Mg of waste input [165] For conversion of ZMSW to ZOFMSW
Boiler fuel consumption	0.08 Mg of coal/ Mg of ZOFMSW Divide the energy requirement per kg of MSW from pilot scale data by Zimbabwe steam coal calorific value of 25.45 MJ/kg [247]
Process water	US$0.60-0.82/m^3 [344] Average water tariff as billed 0.82 and 0.60 US$/m^3 in Harare and Bulawayo respectively.
Price of waste water treatment	US$0.17-0.20/m^3 for disposal [344] Average sewerage tariff as billed 0.23 and 0.17 US$/m^3 in Harare and Bulawayo respectively.
Equipment Cost	Prices are variable depending on quality, sale conditions and other factors

Equipmenttawerytearsyhsrtjhsdtyujedtyusrutws4tyeratyaertyqayqar5aerywrtywy45y4w5

Equipment costs were obtained from current quoted equipment prices from vendors who were identified through www.alibaba.com. Each capital cost element was modelled as a 3-point estimate using a Program Evaluation and Review Technique (PERT) distribution.

A PERT distribution requires parameters for the minimum/pessimistic, mode/most likely, and maximum/optimistic values to define it. It is popularly used in project management applications [345] hence its choice here. Secondly, unlike the traditional method, an estimate of contingency reserves was not included in the initial calculation for total indirect costs since this cost analysis calculates the contingency costs afresh. At the end of the analysis, the traditional contingency reserve, based on rule of thumb approaches, was compared to our estimate. The contingency is the amount of extra funding that may be added to the baseline to guarantee that the budget is not exceeded at a certain confidence level. This is achieved by calculating the difference between the cost at a certain confidence level and the base estimate. Therefore, the higher the confidence level, the greater the amount of contingency needed.

Case- based reasoning was applied in assigning a particular probability distribution to a stochastic variable. For example, a uniform distribution was used to predict and forecast values for the selling price and income from ZMSWH because it would be a new product in the market [346]. Next, random values were selected from the probability models by means of a random number generator, and a profitability measure for each set of values determined under all possible futures. The process was repeated until a plot of return versus the probability of that return being achieved was obtained then the outcome distribution was interpreted.

4.2.1 Capital cost of MSW collection and management fleet

Requirements for the MSW management fleet were based on **Table 4.3** and costs obtained from quotations provided by suppliers. PERT distributions were used for the 3-point cost estimates.

4.2.2 Operating costs for MSW collection fleet

MSW transportation costs include the wages for labor responsible for transporting waste from households to the HTC facilities, technicians who maintain the fleet and operational costs of the MSW fleet. It was assumed that each city or town would convert their existing landfill to a basic transfer station. In particular, the pit station concept in which collection vehicles unload waste into a large pit is envisaged. ZMSW is then conveyed from the pit into an open-top transfer trailer using a tractor or dozer. The pit serves two main purposes, the temporary storage of waste during peak periods and the compaction of the waste [347]. Modern MSW management systems utilize transfer stations as they minimize transport costs, since it is cheaper to haul great quantities of MSW over long distances in large loads than in small ones [348]. Waste collected by refuse compactors would be hauled over longer distance to each HTC treatment facility. The appropriate maintenance of an MSW collection fleet will depend on the ratio of technicians to vehicles so that vehicles are kept on the road and operations run smoothly. The method applied was the Maintenance and Repair Unit (MRU) factor method, which uses an index of the maintenance and repair requirements of a vehicle class relative to a base vehicle class, typically a passenger car. MRU factors by class are then multiplied by the number of vehicles in each class to produce the number of MRUs [349].

Maintenance and Repair Unit (MRU) analysis provides a common basis to estimate the staffing hours required for a particular vehicle type. It allows the comparison of vehicles of varying size and composition. Each different type of vehicle in the fleet is assigned an MRU value. A passenger car is assigned an MRU value of 1.0, and other vehicles are assigned values relative to that. For example, a dump truck requires roughly 4 times as much maintenance work as a passenger car, and its MRU is 4.0 as shown in **Table 4.5**. A passenger car requires 10 - 15 hours of maintenance annually [350]. 1 MRU corresponds to 20 hours in this study. With this number, the total annual workload required to maintain the MSW fleet can be estimated. In order to estimate the workload and technicians needed the total MRU is converted to hours divided by the annual working hours for a technician. An assumption of 1,920 hours per technician per year was used in the estimate. A technician presumably works 8 hours a day, gets 8 holidays per year and 12 vacation days to give 160 hours.

Table 4.3 Stochastic percentage of delivered equipment method

Cost Element	**Fraction of delivered equipment PERT(Min., Most Likely, Max.)**			
Direct costs				**$**
Probabilistic purchased equipment Cost		**E**		
Delivery, fraction of E	PERT(0.10,0.10,0.25)× **E**	**Z**		
Subtotal: Delivered equipment cost	**(E +Z)**			**E'**
			$	
Purchased equipment installation	PERT(0.05,0.10,0.25) × E'		a	
Instrumentation & Controls (installed)	PERT(0.10,0.15,0.18) × E'		b	
Piping (installed)	PERT(0.10, 0.15, 0.20) × E'		c	
Electrical systems (installed)	PERT(0.01,0.05,0.10) × E'		d	
Buildings (including services)	PERT(0.05,0.11,0.15) × E'		e	
Yard improvements	PERT(0.00,0.01, 0.15) × E'		f	
Land	PERT(0.04,0.06,0.09) × E'		g	
Plant Service facilities (installed)	PERT(0.10,0.15,0.20) × E'		h	
Total direct costs (TDC)			**SUM(a:h)**	
Indirect costs				
Engineering and supervision	PERT(0.01,0.10,0.15) × E'		i	
Construction expenses	PERT(0.01,0.05,0.10) × E'		j	
Legal expenses	PERT(0.01,0.01,0.02) × E'		k	
Contractor's fee	PERT(0.17,0.19,0.22) × E'		l	
Total indirect costs (TIC)			**SUM(i:l)**	
Fixed capital Investment (FCI)			**(TDC+ TIC)**	
Working capital (WC)	PERT(0.70,0.75,0.89) × E'			
Total Capital Investment (TCI)			**FCI + WC**	

Table 4.4 Solid Waste collection and landfill equipment of 16 urban councils [38]

Equipment	***Quantity***	
	Existing	**Desired**
Refuse Compactor	70	104
Front End Loader	5	16
Tractor and Trailer	30	37
Dozer/Tracked loader	2	17
Landfill Compactor	1	19
Skip bin	100	220
Skip Truck	7	20
Weigh bridge	0	16
Skip bin and Tractor	5	16

From 2,080 work hours per year (40 hours per week) available, subtract the 160 hours to get 1920 hours per year. 24 technicians are required as indicated by the analysis. Wage cost estimates were based on the Total Consumption Poverty Line (TCPL) reported by the Zimbabwe National Statics Agency [351] respectively. The TCPL, reported to be $US489.60 for Harare in May 2016, represents the total income needed for five members of a household (with all their income added together) as a minimum for them not to be deemed poor. According to the Labor and Economic Development Research Institute of Zimbabwe (LEDRIZ) [352], the national average minimum wage in Zimbabwe is $US263.68 and the national average inclusive of allowances approximately $US336.42 [351, 352]. In this light, the choice of using TCPL for estimating wage costs is reasonable. In contrast direct labor requirement for the plant was estimated using the equation below [282]:

$$\boldsymbol{N_{OL} = \left[6.29 + 31.7P^2 + 0.23N_{np}\right]^{0.5}} \qquad \textbf{(4.10)}$$

where N_{OL} is the number of laborers involved in the process per shift, P is the number of processing steps involving particulate solids and Nnp is the number of equipment handling fluids e.g. compressors, towers, reactors, heaters and heat exchangers. The total number of workers is estimated to be 100 workers per shift at the HTC plants. 1312 direct jobs are estimated to be created (from ZMSW collection to ZMSWH production). Compared to real-world operational data, incinerating 10,000 Mg of MSW creates 1 job; land-filling of 10,000 Mg of MSW creates 6 jobs; and recycling the same amount creates 36 jobs [353]. Our figure of about 17 direct jobs per 10,000Mg appears reasonable compared to other technologies. The higher employment for recycling is attributed to a higher number of activities associated with the process (sorting, transfer and transformation of MSW to new products)

Table 4.5 Summary of MSW transportation costs

Parameter	***Average Value***	***Ref.***
Average annual distance travelled by refuse truck	40,234 km	[176]
Average annual distance travelled by haulage truck	109,685 km	[176]
Fuel Economy of refuse truck	0.92 km/L	[177-179, 354]
Fuel Economy of haulage Truck	2.25 km/L	[354]
Engine Oil Consumption	6.17L per 10,000km	[178]
Maintenance costs (spares, tires, etc.)	> US$7,500 per year per vehicle	[355]
Diesel Pump Price	US$0.92-1.04 per L	[356]
(without taxes and levies)	US$0.59 per L	[357]
HTC plant Labor Requirements and Costs	Calculated separately	
Number of workers per garbage truck, including driver	3	[358]
Assume 1 driver/operator for rest of vehicles		

Table 4.6 Maintenance and Repair Unit (MRU) Factors [349]

Vehicle Class	*MRU Factor*
Passenger Car	1.0
Refuse Compactor	7.3
Farm Type Tractor	1.4
Backhoes, loaders and trenches	2.7
Dozers, scrappers and pavers	3.8
Roller	3.5
Forklifts	0.9
Bucket trucks	3.2
Digger Trucks	4.5
Dump Trucks	4.0
Other trucks	3.6

Assume 20 hours per MRU as the base unit

Table 4.7 Proposed Vehicle and Equipment requirements and corresponding MRU Factor

VEHICLE TYPE	*QUANTITY*	*MRU Factor*	*Total MRU*
Refuse Compactor	208	7.30	1518
Tractor + Trailer	74	2.00	148
Haulage Truck	11	4.00	44
Wheeled front loaders	32	3.80	122
Tracked loaders	34	3.80	129
Excavators	34	3.80	129
Skid steer (Bobcat)	34	3.80	129
Small forklift	34	0.90	31
Transfer Trailer	11	0.60	7
TOTAL	472		2256

Total Hours (20 hours per MRU) = 45120. Estimated number of technicians = 45120/1920 = 23.5 ~ 24 technicians

4.3 Model Validation

Tools for validation include the power law or six-tenths rule, Bridgewater and Lang Factor methods. These shortcut methods have been developed to approximately calculate the total plant cost to be made within ±50% accuracy for preliminary studies [359]. The power law:

$$\boldsymbol{C_2} = \left(\frac{\boldsymbol{s_2}}{\boldsymbol{s_1}}\right)^{\boldsymbol{n}} \qquad \textbf{(4.11)}$$

where C_2 = capital cost of the plant with capacity S_2, C_1 = capital cost of the operational plant with capacity S_1. Reference plants are given in **Table 4.8**

This power law is commonly referred to as the "six-tenths rule" when n = 0.6 to get a rough estimate of the capital cost if there is insufficient data [359]. The Lang Factor method:

$$\boldsymbol{C} = \boldsymbol{F}(\sum \boldsymbol{C_e}) \qquad \textbf{(4.12)}$$

where C = capital cost (including engineering costs), ΣC_e = total delivered cost of all the major equipment items, F = an installation factor (Lang factor), F = 3.1 for solids processing plant

Bridgewater Method as stated in [290]:

$$\mathrm{C} = 1930N\left(\frac{Q}{s}\right)^{0.675} \qquad \textbf{(4.13)}$$

where C = capital cost, s = reactor conversion (=mass of desired product per mass fed to the reactor), N = number of functional units, 1930 is a prefactor

Table 4.8 Reference plants for power law estimation method

HTC Plant/Process	Investment details	References
Loritus	Plant built to process sewage sludge, food waste and animal by-products, and spent mushroom compost with capacity of 10,000 Mg/yr. Capital cost of €3,523732.50	[131]
AVA-CO2	Biocoal production of 8400 Mg/yr from agricultural waste. Investment of €10 million	[360]
SunCoal	55,000 Mg/yr capacity processing organic waste. Investment cost of €15,000,000	[361]
TerraNova® Ultra	Investment cost of €2.7 million to treat 21,0000 Mg/yr of sewage sludge	[362]
TFC Engineering, Kelag AG	An investment €2.7 million to process 10,000 Mg/yr raw biomass	[363]

4.4. Results and discussion

The following section will look at the capital requirements and costs of the ZMSW collection fleet and HTC plants after which the profitability of the enterprise will be discussed. The contingency reserves needed and factors that can improve project feasibility will then be presented

4.4.1 Plant and MSW fleet capital investment cost estimate at commercial operation

The fixed capital investment for Bulawayo and Harare HTC plants are shown in **Fig. 4.2a-d**. In both scenarios the fixed capital investment requirements for the Harare plant can be expected to be roughly 2.5 times that of the Bulawayo plant. By comparison the feed rate for Harare is 2.6-fold higher than that of Bulawayo. Therefore, a constant return to scale for fixed capital costs exists at least up to a scale-up factor of 2.5. This is in line with the finding of [59] who stated that for plant capacities beyond the 100 Mg/day limit, increasing the plant capacity does not change the capital cost per unit output. In other words, a nearly linear relation between capacity and capital cost per unit output exists above 100 Mg/day.

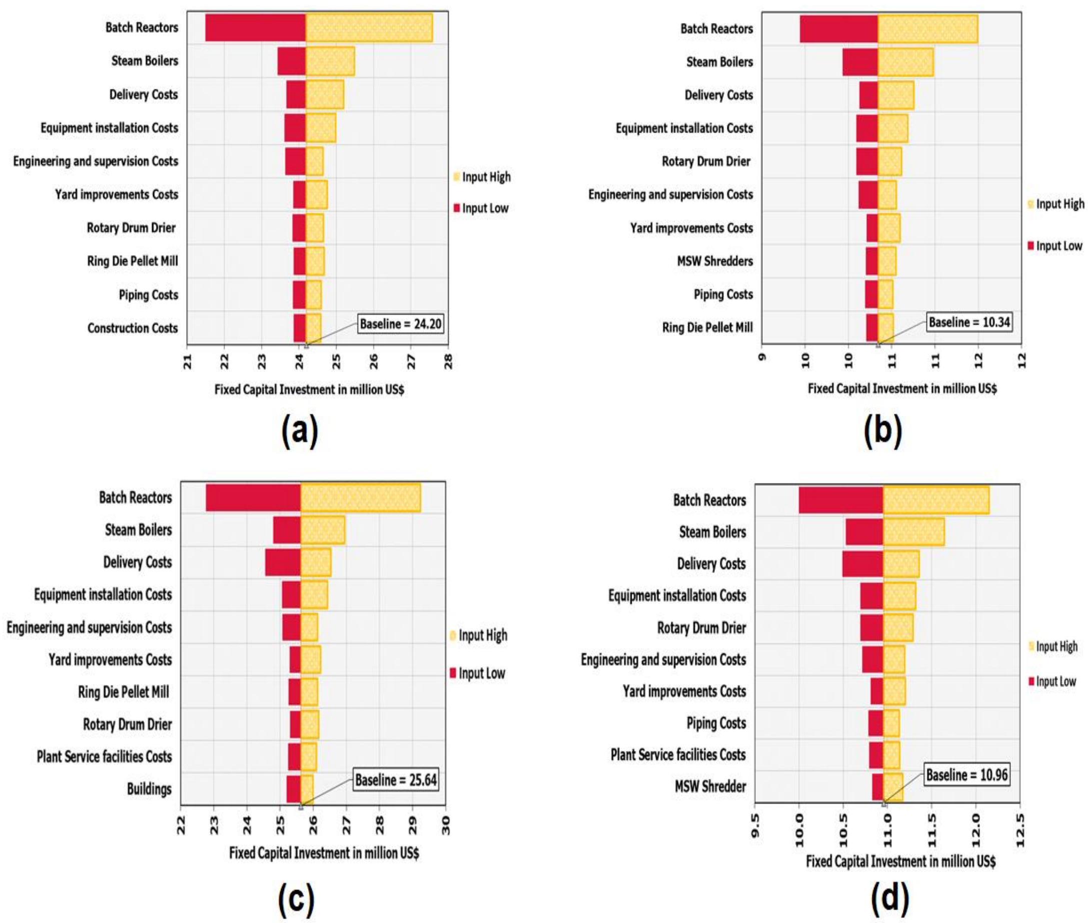


Fig. 4.2 Fixed Capital Costs for a) Harare and b) Bulawayo HTC plants under scenario 1, c) Harare and d) Bulawayo HTC plants under scenario 2

As illustrated in the tornado diagrams, the uncertainty in the cost of batch reactors drives the largest impact. In both scenarios the batch reactor costs had a marked effect on the baseline cost for the fixed capital investments. The total cost of the reactors is in the range of 12.6 – 20.2% and 12.0 – 19.1% of TCI under scenario 1 and 2 respectively. According to Reza et al [130] the reactor represents the major investment cost as it accounts for about 8.5 - 21.3 % of TCI. Specific investment costs of the proposed HTC plants at a 90% confidence interval lie between US$54.11 – 66.95 per Mg of MSW treated for scenario 1. Under scenario 2, a slightly higher investment cost of US$57.23 – 70.89 per Mg of MSW is expected at the same confidence level. With contingency costs, an additional US$24.78 per Mg of treated waste is required under scenario 1 at a 100% confidence level. For scenario 2, US$38.41 per Mg is required for contingencies. A comparison with values from other authors shows the calculations presented here are within the cost ranges that have been reported previously for biomass upgrading using HTC. Lucian and Fiori [364] report a specific investment cost of US$88.69 per Mg of compost and grape marc treated. Berge and Flora [57] estimate a slightly higher investment cost of US$126.10 per Mg of treated food waste, Suwelack et al [61] calculated a cost of US$152.71 per Mg of biogas digestate. Stemann et al [64] calculated a cost of US$251.30 per Mg of palm oil empty fruit bunches. Akbari et al [59] notes that several authors including [64] estimated investment costs from the literature whereas vendor quotations were used in this study. Capex and opex estimates from [57] were based on the work done by [62] who in turn estimated the investment costs using data from the literature.

A quick comparison with conventional WTE technologies reveals that the HTC process is relatively much cheaper. MSW combustion on a moving grate requires an investment of between US$600.00 – 750.00 per Mg of MSW although specific investment costs as low as US$120.00-280.00 have also been reported in more developed nations [365, 366]. A 750 ton per day gasification plant requires a US$150.0 million capital investment [367]. Other studies on hydrothermal conversion reveal that a 100 ton per day HTC plant requires a TCI of US$3.0 million [368]. A privately-owned company, Loritus, was recently awarded € 2.5 million by the EU's Horizon 2020 grant program to build a 10,000 Mg per year plant for a TCI of € 3.5 million [131]. This further demonstrates the relatively lower capital requirements of the HTC process in real world terms.

The city of Harare was considering an investment of US$150 million on a WTE facility to service that area. The joint project with a Dutch company, Integrated Energy BV (IEBV), was poised to operate on a 30-year "BOT" (Built, Operate, and Transfer) basis. The proposed plant would have produced electricity, included a landfill for final disposal of waste after the incineration process, a sorting and recycling plant and wastewater processing plant [369]. The Harare metropolitan area generates 421,757 Mg/yr [145] representing a specific investment cost of about US$ 356 per Mg of annual throughput of MSW. Kumar and Samadder [370] iterates that incineration still remains non-viable for many developing nations due to its high capital requirements and operating costs. HTC can be a much cheaper option as demonstrated in this study. Decision makers have to consider all the possible solutions to avoid unnecessarily high spending using public funds. When analyzing investment data for WTE it is interesting to note the cost variation brought about by the location of such WTE facilities. It cost about US$250 per annual Mg capacity (U$143-320 per annual Mg) to build 60 WTE facilities in China compared to US$840 per annual Mg capacity (US$386-1,811 per annual Mg) to build 21 facilities in the USA. These cost savings even extend to projects led by or with the involvement of Chinese companies when building facilities outside of China [371]. These trends could be expected for HTC as the technology matures and is adopted on a bigger scale in China. Buttmann [362] already reports HTC as an economically attractive option for treating sewage sludge in Jining, China due to lower production costs. Local authorities in developing nations would do better by partnering with Chinese companies to take advantage of the substantial cost savings that can be realized.

The capital investment costs for the MSW collection and management fleet are shown in **Fig. 4.3 a-b**. The total baseline cost was US$27.81 and 34.21 million for scenario 1 and 2 respectively. The cost of garbage trucks is found to mostly affect the baseline under both scenarios. Duties and taxes on imports can have a significant bearing on the capital requirements of private-sector waste operators as shown in **Fig 4.3b**. For example, the duty on a 25-ton garbage truck is 10% and there is value-added tax (VAT) at 15%. The 10% duty is calculated on the Value for Duty Purposes (VDP) which consists of the value of the truck, insurance, freight/shipping and any other charges incurred in bringing it up to the point of importation into Zimbabwe. A truck imported from China with free on board (FOB) price of US$48,900 and shipping costs of US$6,700 will incur the following charges. Cost, insurance and freight (CIF) to Durban will be US$55,600 which is the 'invoice total' used by ZIMRA for duty purposes. A breakdown of other costs; duty is US$8,340, VDP is US$63,940, VAT is US$9,561. The amount payable To ZIMRA is US$17,931 to give a grand total US$73,531. In this example extra charges such as port handling charges, storage charges or any other special handling fees were ignored.

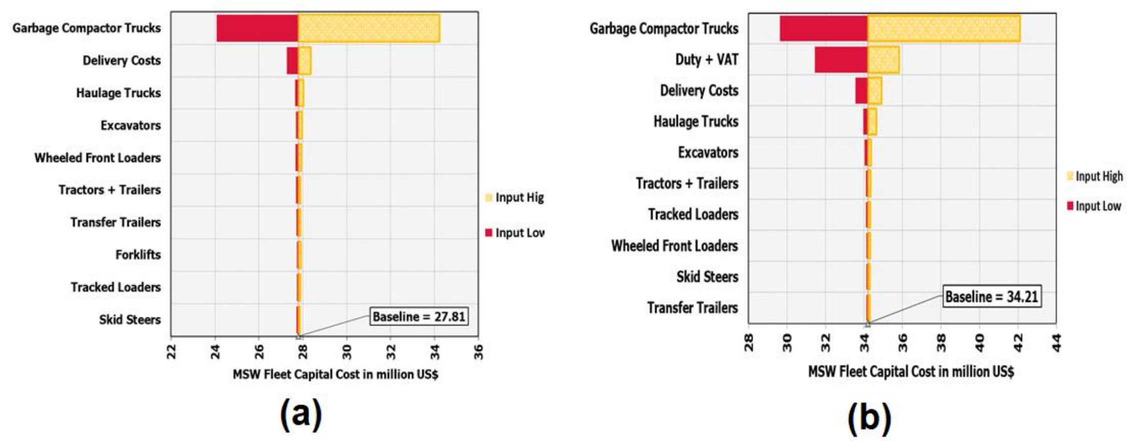


Fig. 4.3 Capital costs requirements for MSW management fleet under a) scenario 1 and b) scenario 2

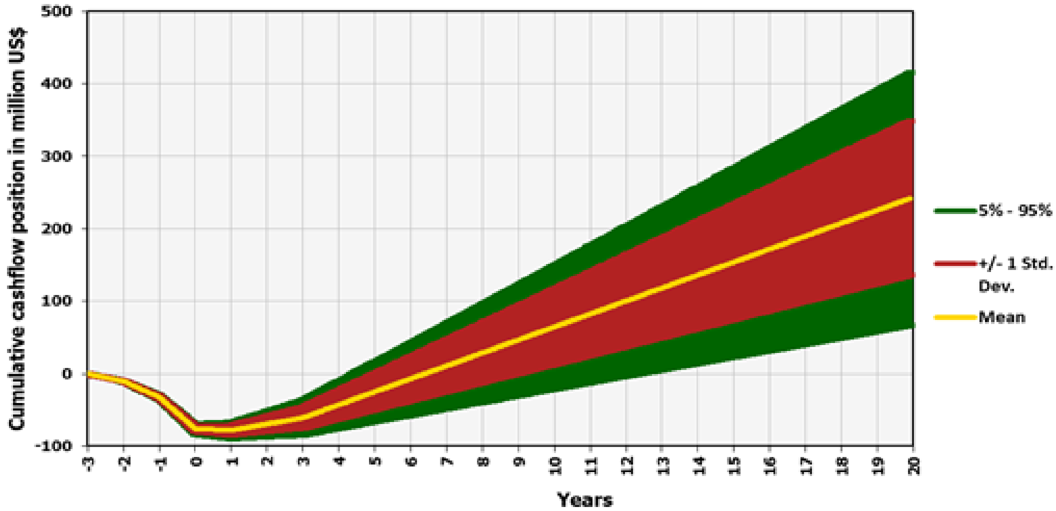
4.4.2 ZMSW collection costs

ZMSW collection costs were estimated to lie between US$24.44 – 30.84 per Mg for scenario 1. For scenario 2, US$28.89 – 33.00 per Mg of ZMSW is needed. This figure is expected to be much lower compared to developed countries. New York City spent US$92.00 per ton for refuse collection in 2016 [372]. Hoornweg and Bhada-Tata [134] estimate that between US$ 20-75 per Mg of MSW is spent on collection in low to lower middle-income countries. It costs about US$31.56 to collect one Mg of waste in Istanbul [373]. MSW personnel labor costs are relatively higher in developed nations because of lower personnel salaries in developing nations hence a lower cost per Mg is expected. From total annual costs of between US$19.98-22.08 million at a 90% confidence level, fuel costs had the biggest effect on the baseline as they would contribute about 65% to the variance of the total under scenario 1. For scenario 2 (US$19.98-22.08 million annually at a 90% confidence level), fuel contributes about 13% to variance. Labor costs have the highest impact on the baseline, contributing 70 % to the variance.

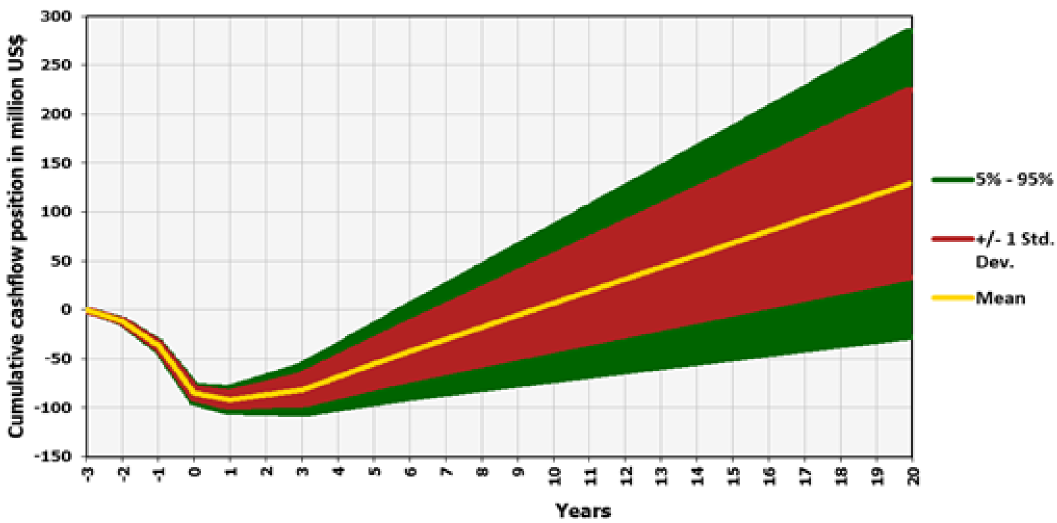
Roughly 32 – 43 % of revenue will be diverted to collecting ZMSW for scenario 1 whilst 37 – 50% of all income will cater for the collection under scenario 2. As most municipalities are struggling to finance waste collection, HTC could provide the extra income needed for the waste management system. According to [374] cities in developing countries spend 77-95 % of their income on collection and substandard disposal. Zimbabwe's situation is more dire as the available funds are just enough to support the collection of waste. There are no excess funds to invest in other subsystems [38]. From the model presented here, roughly 60-84% at a 90% confidence level of income with go towards collection and ZMSWH production under scenario 1. Under scenario 2, 66-92% of the income will be spent on the same costs.

4.4.3 Profitability

Fig. 4.4a-b show a stochastic cash flow forecast under both scenarios. To enable the meeting of short-term obligations and reduce the risk of bankruptcy a stochastic cash flow model is necessary. It becomes especially crucial during uncertain credit conditions. Although our model cannot fully capture all macroeconomic conditions, it is clear from the cumulative cash position diagrams that a private sector run operation carries a lot more risk than a government operation. The expected cumulative cash flow at the end of 20 years is US$244 million (US$67-418 million at a 90% confidence level) under scenario 1. This amount of money is about 3.25 times the mean TCI of the project calculated at the initial time. In contrast for the private sector, at the end of 20 years US$130 million can be expected (- US$28 to 287 million at a 90% confidence level) which is roughly 1½ times its mean TCI requirement. Whilst this analysis did not consider the time value of money, the profitability measures including time value of money (NPV and IRR), with annual end-of-year cash flows and discounting are depicted in **Fig. 4.5a-h**. Risk analysis indicates that there is an 55 % chance of achieving a positive NPV for the government. With a 90% chance that ROI will lie between 5.4-29.0 % and IRR of 5.2-22.9 % (mean 14.6%). The private sector would be incapable of operating profitably as the odds of a positive NPV are significantly lower at 18%. The ROI can be expected to lie between -0.8 and 18.2 % at a 90% confidence level. A much lower IRR of 7.9 % is expected. Mean projected IRR is greater than the cost of capital under scenario 1, the government could potentially accept the project as a good investment. A large-scale HTC system is not a viable undertaking for the private sector.



(a)



(b)

Fig. 4.4 Cumulative cash position over the 20-year span of the plants under a) scenario 1 b) scenario 2

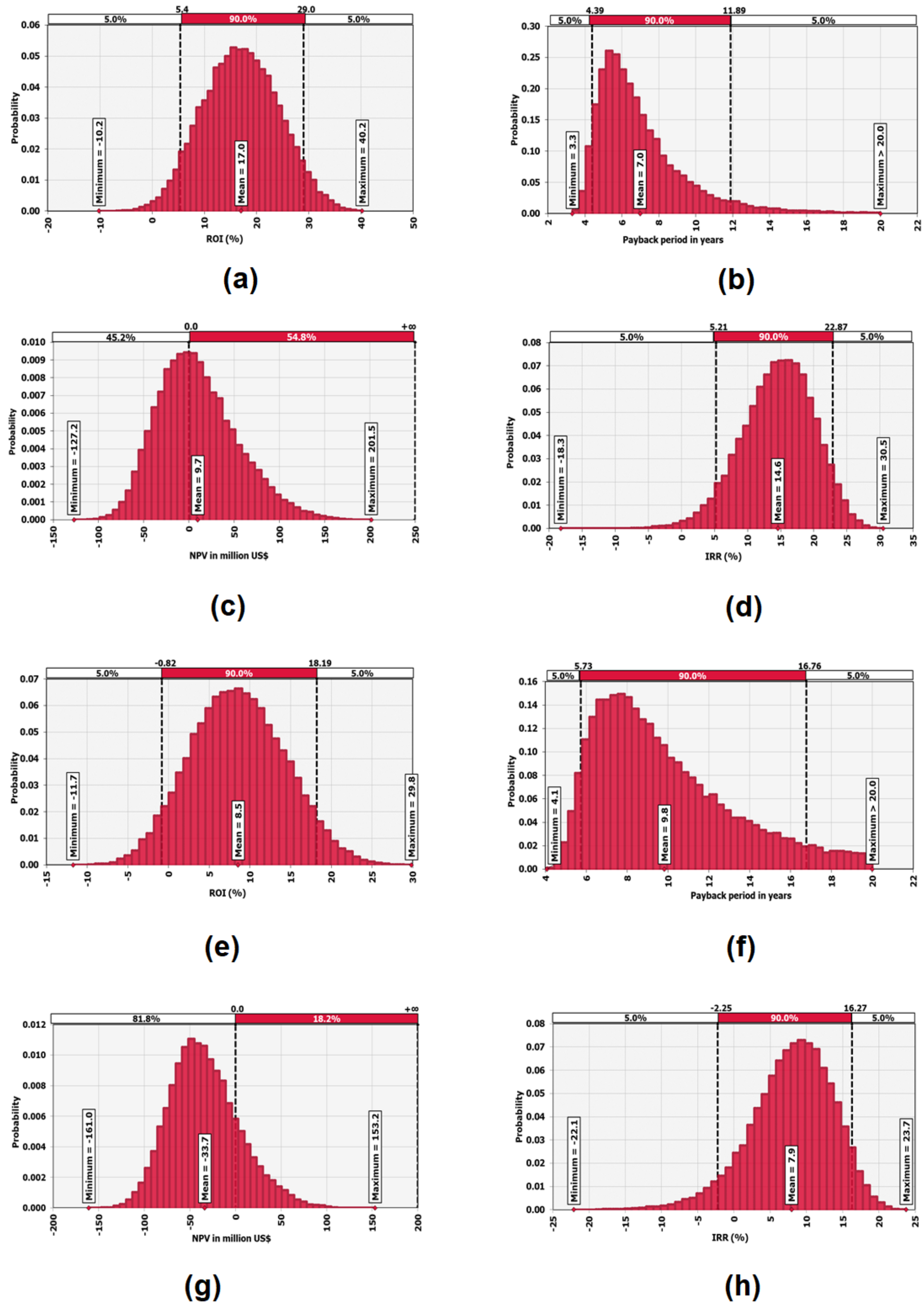


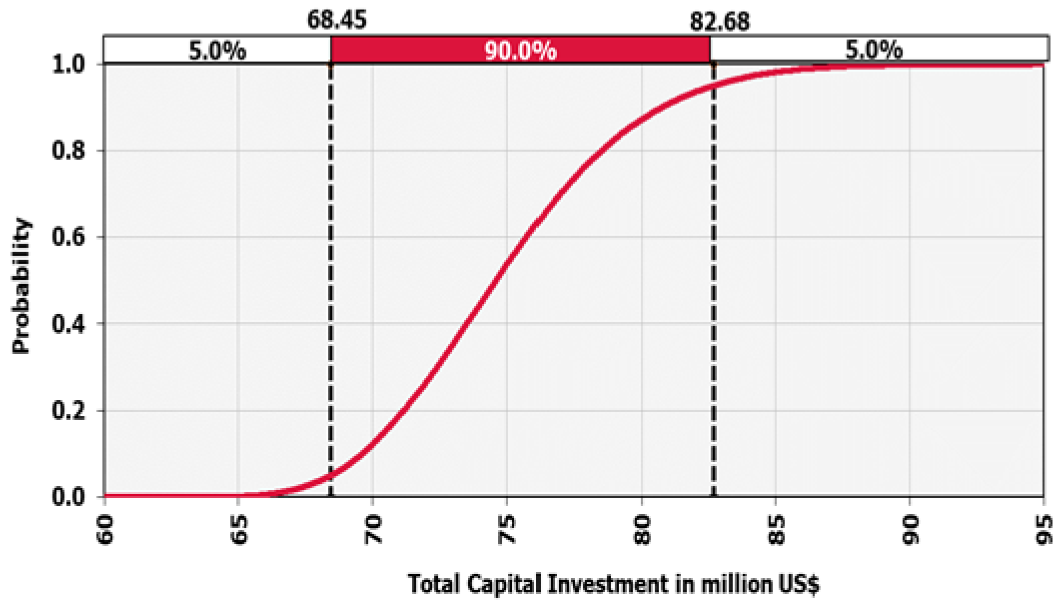
Fig. 4.5 Measures of profitability under scenario 1 (a-d) and scenario 2 (e-h)

4.4.4 Contingency Estimates

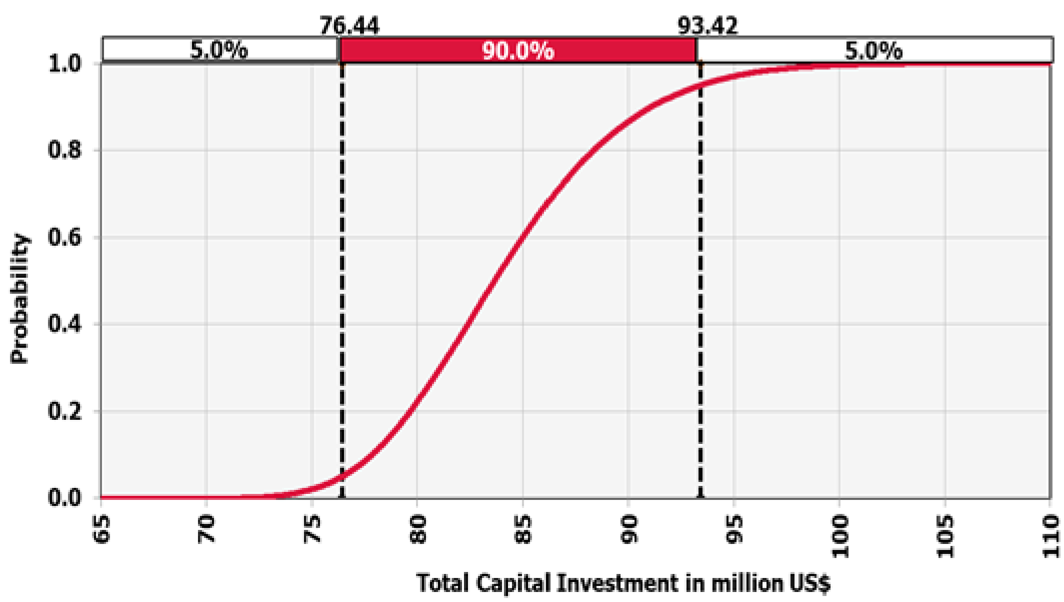
The TCI for the HCT plants and MSW collection system is about US$ 74.9 and 84.1 million for scenario1 and 2 respectively without contingency. TCI cumulative probability curves are depicted in **Fig. 4.6a-b**. Plot of confidence level against contingency is shown in **Fig. 4.7**. Using the Peters et al method [281], the contingency reserves needed for scenario 1 would be about US$14.8 million corresponding to roughly an 87% confidence level in the modified method. The suggested contingency at a 100% confidence level exceeds the traditional method by a factor of 2. For scenario 2, the traditional method will require US$17.3 million set aside for reserves corresponding to about a 45% confidence level. To raise it to 100%, an additional US$27 million would be required. Our findings seem reasonable given that projects in the chemical process industries typically overrun their budgets, including contingency, by 21% and 10% of large projects overrun their budget by more than 70% [375].

4.4.5 Recommendations for improving the commercial performance

From a pure economic sense, deriving from the results presented here, an HTC based waste to energy system is likely to succeed if run as a parastatal. Given that it is an explicit part of the government's mandate to be the provider of critical services to the public, even with the 55% probability of economic success HTC could be implemented. The government can leverage on its ability to subsidize its operations. The private sector is likely to suffer huge losses unless given grants or a full waiver on income tax, value added tax, excise duty, etc. ISWA [376] argues that since subsidies and exemptions can change abruptly it is imperative that the commercial viability of WTE facilities be independent of such forms of financial aid. In unison, [377] asserts that subsidies have had an adverse effect on the adoption of new technologies as they create transient and unsustainable economic conditions that have fended off investors and consumers. Zimbabwe's parastatals however, have a long history of incurring heavy losses and poor service delivery due to gross mismanagement [378]. Zimbabwe's approach to adopting HTC should reduce the financial risk associated with WTE projects. Local governments can share the economic burden along with private investors thorough concessions or Build–



(a)



(b)

Fig. 4.6 TCI for combined HTC plants and MSW collection system under a) scenario 1 and b) scenario 2

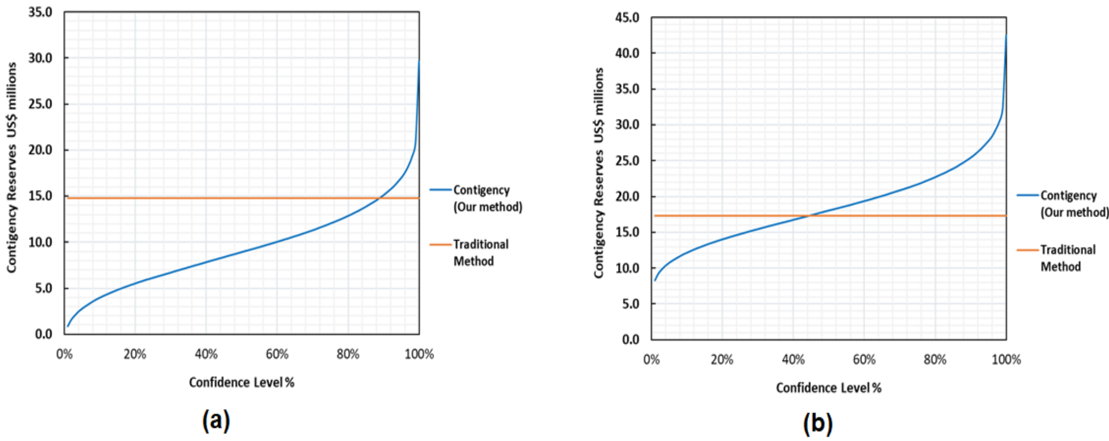


Fig. 4.7 Contingency estimates based on confidence level under a) scenario 1 and b) scenario 2

operate–transfer (BOT) framework. This would more likely encourage investment as it signals the government's commitment and confidence in the project. This can inject much-needed expertise from the private sector into local waste-management systems. Such private-public partnerships (PPP) could lead to increased organizational performance and effective governance. The establishment of a PPP regulatory framework for MSW management infrastructure and services, has not been enough to encourage the adoption of WTE in developing countries like the Philippines though. The Ayala Alabang and Baguio biomethanation projects all reached an impasse despite agreements between local governments, civic groups and US-based investors due to unforeseen circumstances. Barriers included a lack of confidence on WTE's ability to tackle the waste problem, misgivings about investors potential to influence local politics and obstructions from those who felt unrepresented in the agreements and stood to lose out such as waste pickers at dump sites. One opponent, a Non-governmental organization (NGO) protested against WTE citing its legitimization of waste generation and its disruption of established and traditional composting activities. Investors contended that the Baguio project was deliberately undermined by authorities who demanded bribes which the investor was unwilling to pay [379]. This highlights the need for capacity building for new technologies as a lack of understanding of the socio-economics and apprehensions of the host communities can hinder technology transfer.

Alternatively, the enterprise can be run as a strategic parastatal where a more concerted effort to improve management, efficiency and profitability is sought after whilst still remaining under government ownership. Even with adequate financing without the necessary institutional reforms the success of any waste management system can fail. As noted by [380], the World Bank has financially supported solid waste projects in the past with no improvement in the quality or efficiency of the services. [380] further goes on to identify key areas that need to be improved in developing countries. These include legislative aspects, institutional structure and responsibilities, technical and managerial proficiency, correct vehicle specifications with transparent and clear procurement procedures, proper maintenance of vehicles in operating condition, adequate pricing for better cost recovery, and the optimal siting of selecting and acquiring sites for transfer stations. Muswere and Rodic-Wiersma [381] assert that there is appropriate legislation on waste management in Zimbabwe, the authors site the lack of experts, adequate supervision and training of staff as a major impediment.

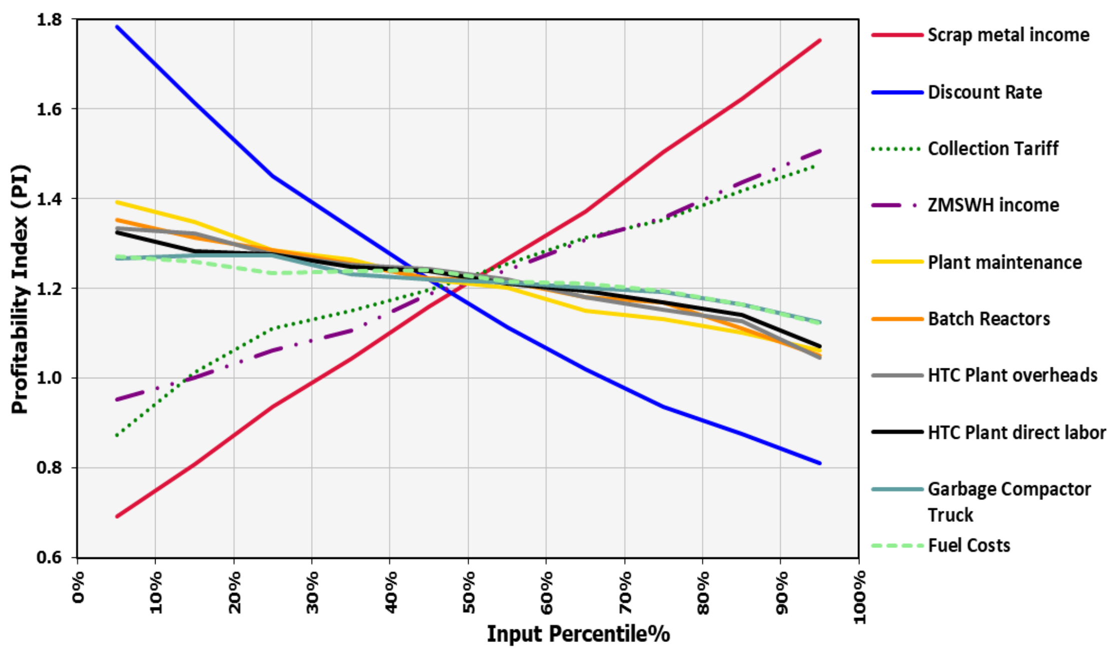
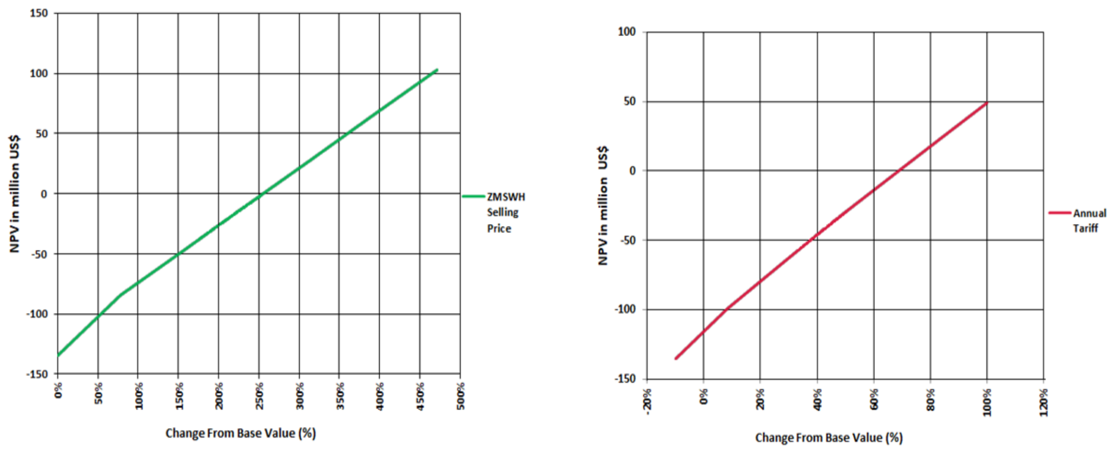


Fig 4.8. Spider plot of profitability index against its top driving factors

These authors go on to recommend that policies need to focus on preventive maintenance of vehicles and equipment instead of the reacting to breakdowns. However, in partial disagreement, ZELA [382] asserts that there is no comprehensive policy on biofuels production despite Zimbabwean government's support of bioethanol and biodiesel projects. Such issues if not addressed may impede bioenergy technologies such as HTC.

A spider plot of Profitability Index (PI) against variables that have the greatest influence on the output PI is shown in **Fig. 4.8**. The income from scrap metal is most influencing the PI because it covers the largest vertical range, and as it increases, so the PI increases. Income from scrap metal would be a major cost recovery system in place, however, due to its volatility, may not be so reliable. Whilst the creation of numerous hedging strategies has been instrumental in averting commodity risk, this may not be guaranteed for scrap metals [383]. Scrap metals with a lower level of metal purity are traded at a discount. Where purity levels are higher or where there is a high rarity factor, a premium is added. Variances relative to the base metal price, if volatile, may be difficult to hedge against. The structuring of commodity contracts in scrap metals is outside the scope of this article and readers are encouraged to get more information from [384]. The discount rate is of the utmost importance because the higher it gets, the lower the PI becomes. A high discount rate is warranted due to the prevailing fragile macroeconomic environment and business climate which would undoubtedly engender an inconducive platform for WTE technologies. This is a major deterrent to attracting foreign investment thus decreasing the chances of successful concessions. Discount rate is largely a function of the perception of risk. By entrenching the protection of human and property rights investors perceive a lower risk of expropriation and infer a low discount rate. The other cost recovery system would be the income from selling ZMSWH and ZMSW collection tariffs. The two have a similar relationship but slightly less influence on PI. In our model ZMSWH selling price was assumed to be lower than coal to confer a competitive advantage to the product.



(a) (b)

Fig. 4.9 a) Sensitivity percent change graph for ZMSWH selling price against minimum NPV (Base value=US$35) b) Sensitivity percent change graph for ZMSW collection tariff against minimum NPV

However, ZMSWH selling price was varied was up to 470% while keeping all the other parameters the same. As seen from **Fig. 4.9a** a 260% increase from the base price guarantees that the minimum NPV is zero or greater. The minimum selling price of ZMSWH would have to be about US$91 per Mg for the recovery of all costs. The market would unlikely be willing to pay a price premium on the green product as this would be about 30% higher than the price of coal. Whilst the volatility risks to the price of scrap metal would be beyond the control of the government, tariffs are a driving factor which could be optimized. Compared to other countries in the African region, Zimbabwe's fees are low. In Accra, Ghana, low-income households pay US$4.00 per month and high-to-middle-income earners pay an average of US$6.67 per month [385] almost 50% higher than in Zimbabwe. Revenue streams can be increased by improving waste fee collection. A sensitivity analysis was carried out to determine the effect of this increase on the minimum value of NPV. This depicted on **Fig. 4.9b**.

The model estimates that a 70 % rise in the collection tariffs ensures the minimum NPV is zero or greater. While revenues from tariff collection would also depend on the fee collection rate, deficits would need to be provided by governmental tax money. One other option to increase ZMSW collection fees would be the mandatory use of pre-paid designated garbage bags. In addition to the basic service charge, each household would pay according to the volume of their own solid waste, by buying specially designated garbage bags. This increase would require a strong political will and public acceptance. For the other factors such as costs of garbage collection fleet, reactors, etc. better prices from suppliers can be obtained through better negotiation. Conclusions drawn from our previous paper [247], reveal that HTC can produce clear environmental benefits through significant reductions in the methane potential of ZMSW. It is crucial and in the interest of all that the Zimbabwean government and the private sector form an alliance in order to reach a more sustainable solution.

4.4.6 Validation of results

To confirm the validity of the probabilistic percentage of delivered equipment cost method, the calculated capital cost was compared with values from three other methods.

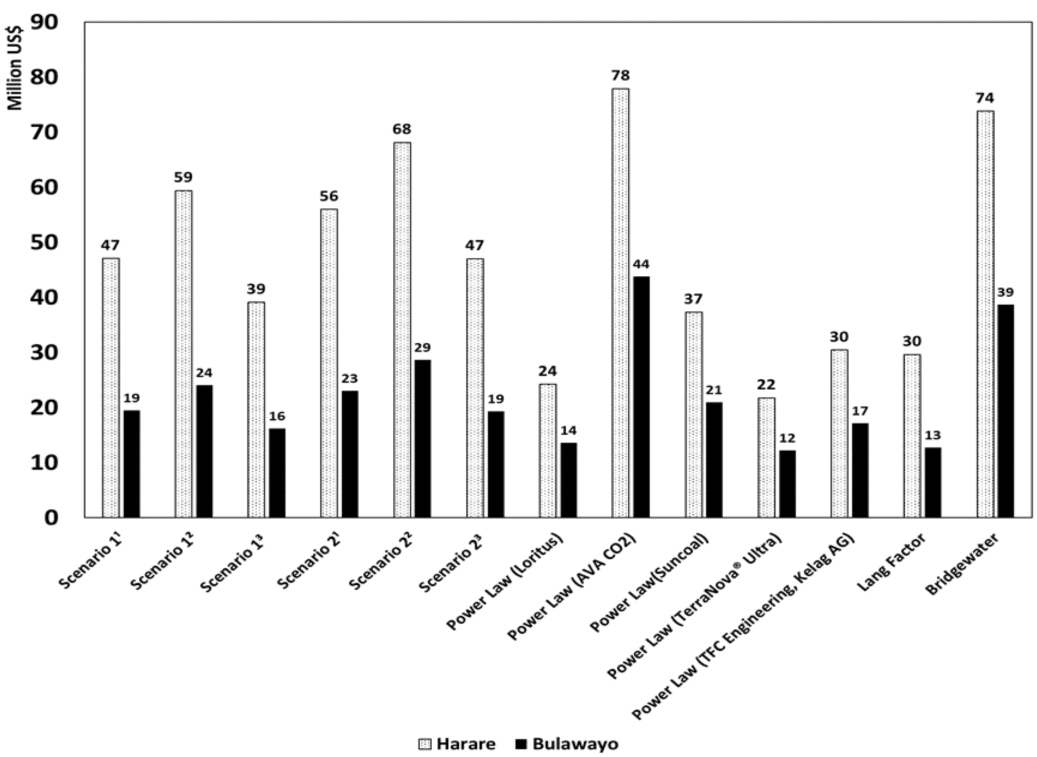


Fig. 4.10 Validation of HTC plant capital cost estimations. Point estimates in this study based on ^{1} mean, ^{2} maximum and ^{3} minimum estimates from Monte Carlo simulations plus contingencies

The comparisons are shown in **Fig. 4.10**. There is generally good agreement, giving credence to the methodology presented in this study. While the figure from the power law Power Law (TerraNova® Ultra) seems a bit on the low side, it is, nevertheless, in the ballpark area. It must be noted that the power law required no design information other than the production rate and investment cost of existing plants. The Bridgewater and Power Law (AVA-CO2) estimates are the largest compared to the other methods. Despite the large disparities between these techniques and the method presented in this study they are still within the specified error range. Variability in the Bridgewater equation is introduced by the prefactor and exponent whose values are obtained from cost correlations for petroleum processing plants meaning correlations may not be accurate for other processes. The Bridgewater method also leaves it to the discretion of the estimator to determine the major steps of a production process. AVA-CO2 process is unique from the other plants because of a phosphorus recovery step using their "AVA cleanphos" process. The phosphorus is recovered not from sewage sludge or sewage sludge ash, but directly from the HTC hydrochar [386]. This can add to the overall capital cost requirements leading to a higher estimate when using the power law. In general, the power law and Bridgewater method are the easiest to implement, however, they are the most inaccurate. The methodology presented in this paper allows for a detailed accumulation of equipment costs, which can be continuously modified throughout the development of a project. Due to its stochastic nature it creates a range around a point estimate that reduces the overall error in the estimation, as overshoots will be corrected by undershoots leading to more overall accuracy at the project level. Although the probabilistic percentage of delivered equipment cost method is detailed it is also the most time consuming compared to other methods.

4.5 Conclusions

Waste accumulation and waste management problems have not only been an unsustainable burden on the environment but a scourge that has led to thousands of casualties in Zimbabwe. The establishment of a successful waste management system cannot be overemphasized as the current approach is struggling to cope. An economic assessment of a proposed HTC-based system on a national scale based on pilot data has been presented. HTC, an up-and-coming technology in MSW beneficiation, is particularly suited for high moisture feedstock such as MSW, as it a water-based technology that produces a coal-like product (hydrochar). The environmental impact of HTC was priorly investigated, this study focused on the economic feasibility of the process in Zimbabwe. Two scenarios were presented, the first assuming a government run HTC system and the second a fully privatized operation. Using a modified purchased equipment cost method involving probability models and Monte Carlo simulations, the economic viability was evaluated assuming a project life of 20 years. Generation of positive NPV is not possible for the private sector. Risk analysis indicates a very low probability of success (18%) for a positive NPV. The calculated 90% confidence interval indicates that the TCI would be US$ 76.4-93.4 million with an ROI ranging from -0.8-18.2% and IRR of 7.9 %. Under the government-run system, there is a 55% probability of a positive NPV assuming a zero corporate tax rate and full waiver on import duties. At a 90% confidence level ROI will be 5.4-29.0 % and IRR of 5.2-22.9 % (mean 14.6%). TCI for the HCT plants and MSW collection system is about US$ 74.9 million or about US$54.11 – 66.95 per Mg of MSW treated. Contingency reserves needed would be about US$14.8 million using the traditional method. Approximately US$29 million is needed for contingencies based on probability modelling. To further guarantee a high level of success (minimum NPV>0), a 70% raise in ZMSW collection fees from households would be required. Alternatively, a volume-based bag system for revenue raising is suggested. HTC on a national scale would stand a better chance, however, if there is an alliance between the government and private sector to avert serious challenges rooted in poor cooperate governance in state run enterprises. The private sector can bring much-needed specialized and well-placed managers to reduce inefficiencies whilst government can extend subsidies or exemptions to ensure financial viability. There are a few points to note with regard to the limitation of this paper. This economic evaluation is narrow in that it considers economic viability on the investor side. The study did not consider the broader socio-economic impact of HTC. The socio-economic impact is mainly influenced by the local and regional frameworks including the educational level, national policies on the environment, social targets, cultural attitudes and values. From a socio-economic study, which requires an elaborate study in depth, the impact of HTC can be integrated into the political, social and economic system of Zimbabwe. The participation and support of the community for a shift in the current waste management system to an HTC based system is needed. An assessment is necessary to gauge people's ability, openness and willingness to pay for an improved waste management system. The policy and regulatory framework on biofuels in Zimbabwe is not adequate enough to provide the necessary drivers to accelerate the development of WTE. A social cost-benefit analysis can compare the cost and monetized benefits of new policies and the optimal choice for the WTE technology that should be adopted. This study can serve as a foundation for such studies.

Chapter 5: Estimation of avoided leachate produced from uncontrolled landfill disposal sites

Chapter 5 focuses on how much leachate generation can be avoided by introducing a WTE strategy in Zimbabwe. This chapter is related to Chapter 3, in that it is looking at the environmental impact HTC can have on leachate generation by averting landfilling.

5.0 Introduction

Landlocked and situated on the southern hemisphere, Zimbabwe is a country troubled by environmental degradation due to poor waste management. With a total land area of 390,757 km^2, the nation is bordered by Mozambique, South Africa, Botswana, and Zambia to the east, south, west and north respectively. According to census data, Zimbabwe's population reached 7.7 million in 1982. The country's first 10 million was reached in 1992 with the 15-million mark surpassed in 2015. The urban population has grown from 1.6 to 5.2 million between 1980 and 2016 [193, 194] and with it a lot of challenges for local authorities who have largely been incapacitated to effectively handle the solid waste generated. This has been compounded by an ailing economy which saw a sharp decline in GDP per capita between 1980 and 2009 [195]. Local authorities lack adequate infrastructure, financing and labor amongst other factors. These complexities have adversely affected the waste management system which is characterized by low collection efficiencies, high crude tipping rates, on-site burning of waste, and the buildup of garbage in drainage systems, waterways, and streets [9]. Landfills are prevalently used for final MSW disposal albeit without the necessary leachate collection systems in most sites. Nearly 98% of these landfills are not sanitary [38] but are open dumps as little to no final cover is applied. One of the largest dumps is Pomona located in the capital city as shown in **Fig. 55.1**. There are reports of groundwater contamination verified by rising levels of trace elements such as lead mainly due to the unconfined leachate entering potable water sources from nearby landfills [42, 196, 197].

A quick survey of the scientific literature reveals that few attempts have been made to quantify the leachate discharged from Zimbabwe's landfills, the intricacies of which are magnified by the lack of a historical solid waste database. This has made the quantification of the amount of MSW landfilled and leachate generated therefrom difficult. Reports that have been trickling in since the early 2000s have focused on Zimbabwe's solid waste composition, energy potential, its impact and possible solutions and technological remedies to challenges encountered in the sector [9, 30-52, 54]. Due to a lack of field monitoring data to evaluate seepage from the existing landfills and limited studies on the estimation of leachate generation from Zimbabwe's landfills, this study will bridge a gap for other environmental studies. This paper could help in the investigation of groundwater vulnerability in the vicinity of landfills and to estimate the cost of remediation or setting-up of landfill leachate collection systems.

Approaches to predicting leachate generation categorically fall into either of the following five groups: the water balance method, computer modeling- water balance method combinations, empirical equations, mathematical models and direct infiltration measurements [198]. Zimbabwe is classified as a semi-arid country with at least 85% of the country receiving no more than 800 mm of rain annually. Furthermore, rainfall is concentrated between November and March [199]. Atmospheric precipitation can thus be expected to contribute to leachate generation as landfills are of inferior design. The Water Balance Method (WBM) adopted in this study can allow a relatively simple computation compared to the other methods.

Fig. 5.1 Maps showing location of Pomona dumpsite in Harare. The city of Harare is the largest in population size and area. The city is located at 17.8° S, 31.0° E. On the north-east side, on the outskirts of Harare, Pomona municipal landfill is neither lined nor covered daily.

WBM is particularly appropriate for landfills in which a relatively high permeable layer of soil is used as final cover. An outstandingly lesser quantity of water would infiltrate into a landfill if a low permeability synthetic membrane were used as covering. Despite the extensive use of WBM, field verification has revealed significant margins of error between the predicted and actual leachate quantities [198]. Too often, minimal account is taken of the uncertainty surrounding the spatial and temporal heterogeneity that characterizes the leachate generation process when approximations are made. The limitations of conventional prediction techniques emanate from their deterministic nature. This makes these models insensitive to uncertainty. The amount of avoided leachate generation after the introduction of HTC will be estimated by calculating the current leachate generation rate from Zimbabwe's landfills. The objective of this chapter is therefore to introduce a stochastic approach to the quantification of MSW generated and subsequent leachate generated. This will be achieved through the use of probability models supported by 10,000 Monte Carlo simulations.

5.1 Materials and Methods

A WBM model was developed on a spreadsheet equipped with Palisade's @Risk software [200], a risk analysis plugin capable of performing Monte Carlo simulations. The Monte Carlo method is deployed when an approximate solution to a mathematical problem that is difficult to solve analytically is required. Typically, experimentation would be time-consuming, costly, or unfeasible for such a problem. The problem may contain elements that exhibit chance in their behavior. The idea behind these simulations is to generate values for uncertain elements in the model (the inputs) through random sampling. The basic steps involve modelling a system as a series of probability density functions (PDFs), repeatedly sampling from the PDFs and analyzing the outcomes [201, 202]. The greater the number of runs the greater the confidence in the result. Since statistical sampling experiments are performed on a computer, time and resource savings can be attained as @Risk eliminates the need to run, test, and present several spreadsheets.

In simple terms WBM states:

$$L = P - RO - ET - \Delta S - G \qquad (4.1)$$

where L = post closure leachate volume per unit surface area of landfill (mm), P = volume of precipitation per unit surface area of landfill (mm), ET = volume lost through evapotranspiration per unit surface area of landfill (mm), RO = volume of surface runoff per unit surface area of landfill (mm), ΔS = gain in moisture storage within soil and waste in a unit volume of landfill (mm) and G = volume of water consumed in landfill gas formation per unit surface area of landfill (mm)

The determination of these parameters is outlined in the following subsections.

5.1.1 Prediction of cumulative MSW generated and landfilled

Total MSW generated since 1980 was estimated using historical urban population data provided by the World Bank and per capita MSW generation data. The latter was estimated by first defining a probability distribution using @RISK's built-in distribution fitting feature on reported per capita generation values shown in **Table 3.1**. The annual quantity of landfilled MSW was determined by multiplying together the following terms by 365: total population, rate of urbanization, per capita MSW generation (probability distribution function) and collection efficiency (probability distribution function).

A variation of a triangular distribution, called Trigen in @RISK [203] was used to model the collection efficiency defined by Trigen(a, b, c, p, q). The parameters represent the following: a is the practical minimum, b the most likely value, c the practical maximum value, p is the probability that the parameter value could be below a and q is the probability that the parameter value could be below c. Collection efficiencies dropped from at least 80% (in the mid-1990s) to as low as 30% in the mid-2000s [41]. Other reports cite the efficiency between 50 and 85% [38, 50, 52]. Therefore for this study, Trigen(0.3, 0.75, 0.8, 0.1, 0.9) was assumed.

5.2.2 Estimation of evapotranspiration

Thorntwainte's equation below was used to estimate ET. This is an indirect way of determining ET and the use of this equation which is inherently simple gives justifiable good results [204]. Direct methods of measuring ET are often expensive, highly demanding in terms of accuracy of measurement and require well-trained researchers. Other indirect methods (empirical or semi-empirical equations) are only valid under specific climatic conditions and sites [205]. The complexity of alternative models or direct methods does not translate into more accurate results hence the choice of this equation. Instead of deterministic values for the terms in equation 4.2, probability distribution models defined from historical rainfall, temperature patterns and daylight hours were used. Akaike's Information Criterion (AIC) determined the best fitting distribution model.

$$\mathrm{PET} = 16 \times \left(\frac{L}{12}\right) \times \left(\frac{N}{30}\right) \times \left(\frac{10T_\alpha}{I}\right)^{\alpha} \qquad (4.2)$$

where PET is the estimated potential evaporation (mm/month), T_α is the average daily temperature of the month being calculated (℃), N is the number of days in the month being calculated, L is the average day length of the month being calculated (hours), $\alpha = (6.75 \times 10^{-7}) \times I^3 - (7.71 \times 10^{-5}) \times I^2 + (1.792 \times 10^{-2}) \times I + 0.49239$ where $I = \sum_{i=1}^{12} \left(\frac{T_{ai}}{5}\right)^{1.514}$ is the heat index which depends on the 12 monthly mean temperature T_{ai}. ET was estimated by assuming a uniform distribution, with limits 0<ET < PET. ET is unpredictable but is always less than or equal to PET.

5.2.3 Estimation of runoff and volume of water consumed during landfill gas formation

Typically, runoff coefficients range from 0.05 to 0.75 [154] hence a uniform distribution was assumed between these values. Ehrig's and Cossu et al. equations [206] below were used to estimate G. The mass of water consumed per m^3 of landfill gas produced (W) is given by

$$W = \frac{(4a - b - 2c + 3d) \times (\frac{18}{4}) \times 1000}{(12a + b + 16c + 14d) \times G_e} \qquad (4.3)$$

where Ge is the total gas quantity in m^3/Mg of MSW ($C_aH_bO_cN_d$) given by Ge = 1.868× C× (0.014 T+0.28). C is the Total Organic Content (TOC) (kg/Mg of MSW) and T is temperature in ℃. An approximate chemical formula was calculated for MSW using typical ultimate analysis data and Zimbabwe MSW composition data reported by [10, 30, 31, 33-37, 40, 41, 148, 207, 208]. G was then calculated by dividing volume of water consumed by landfill surface area as shown in equation 4.4.

$$\text{Landfill surface area} = \frac{1}{\text{depth of landfill (m)}} \times \frac{\text{landfilled}-\text{MSW (tonnes)}}{\text{density of waste (tonnes/ m}^3)} \qquad (4.4)$$

Uniform distributions for depth and landfilled-MSW density were used with of limits 3-6 m and 534-1000 kg/m^3 respectively.

The following assumptions were made in developing the model: the only source of infiltration is precipitation falling directly on the surface area of landfill, groundwater does not enter the landfill, all water movement through the landfill is vertically downward, leachate recycling or co-disposal of liquid do not take place and the landfill is at field capacity at the start of calculations. Meteorological data are site specific, but due to unavailability of landfill site data, weather bureau data were used in line with common practice [154].

5.3 Results and Discussion

Results from 10,000 iterations are shown in **Fig. 5.2 - 5.4**. The trend in MSW generation from 1980-2015 depicted in **Fig. 5.2** shows that the quantity of MSW has been increasing steadily. The black region represents the 5 - 95 percentile and the grey depicts the 25-75 percentile for the simulations. The mean is the most-likely estimate of MSW generation. As shown in **Fig. 5.3 a**, on average, about 291,259 – 540,037 Mg/yr. of MSW has been landfilled since 1980. This amounts to roughly 13-16 million Mg of MSW in total since 1980. Using deterministic models, roughly 989,000 Mg and 490,000 Mg were generated and landfilled in 2012 according to a study by [52]. Analysis of reported values reveals an average composition of 32.4 % putrescibles, 16.2 % plastics, 8.6% miscellaneous, 19.9

% paper and cardboard, 6.9 % metals, 4.0 % glass and ceramics, 2.1 % leather and rubber, 3.1 % textiles, 4.1 %-yard waste and 4.5 % wood.

Reported MSW generation per capita (kg/capita/day) figures follow a normal distribution with μ and σ of 0.53 and 0.14 respectively. The calculated molecular formula in this study is C_{617} H_{1718} O_{620} N_{18} Cl_7 and landfill gas (CO_2 and CH_4) quantity generated, Ge, is 81.8 m^3/Mg of MSW. Previously [52] reported 66.7 Nm^3 CH_4/Mg MSW being generated.

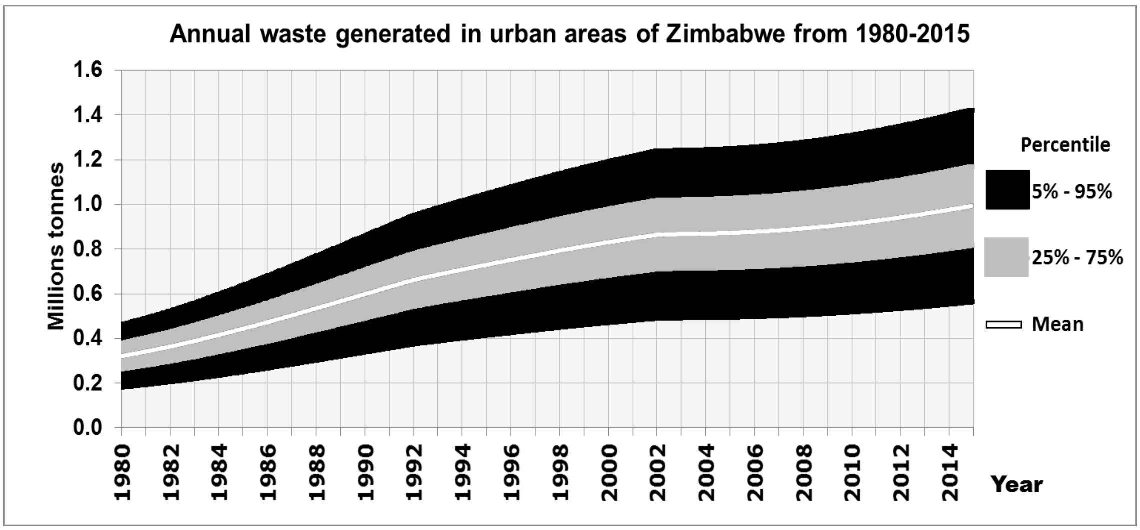


Fig. 5.2 Summary trend for annual MSW generated

Calculated TOC and W are 74.7 kg/Mg of MSW and 1.24 kg water/m^3 of landfill gas. At a 90% confidence interval, 1.07-1.37 billion m^3 of landfill gas can potentially be released. Since most landfill sites are open dumps (where aerobic conditions prevail), the predominate gas emitted is likely to be carbon dioxide. The volume of leachate generated is 1.19- 3.74 million m^3/yr at a 90% confidence level as shown in **Fig. 5.3 b**. This amounts to about 41 – 128 million m^3 of leachate discharge in total since 1980. The high variability of leachate produced from the landfills can be attributed to the variation inherent to leachate generation which relies on hydrologic and climatic influences.

In another study, the average leachate volume discharged from a landfill in Harare (capital city) during the period 1983 to 2014 was estimated to be 94,486 m^3/yr [209]. There are at least 20 official dumpsites corresponding to each urban settlement in Zimbabwe and countless illegal sites hence the confidence in the estimates presented here. There is also reasonable agreement with the rule of thumb approach of assuming 0.2–1.0 m^3 of leachate being generated for each cubic meter of waste landfilled [210]. Since no compacting, sealing, or leachate collection or methane capture is exercised in most of Zimbabwe's landfills, there lies a much greater potential for leachate generation than would for a proper landfill. **Fig. 5.4** is a cumulative distribution of the stochastic water balance. At a 90% confidence level, 381-571 mm per year of leachate is discharged as shown in **Fig. 5.4** ET lies between 390-707 mm. The average annual ET in neighboring South Africa was estimated to be 303 mm [211] for 2000–2012 using a different technique. This falls well within the range shown in **Fig. 5.2**.

Assuming that HTC averts this same amount of MSW from going to the landfills, the amount of avoided leachate should fall into the same range. On average, 2.23 million m^3/yr of leachate can be avoided by averting waste from the uncontrolled landfills to HTC facilities. This can significantly reduce a major environmental and health risk associated with uncontrolled landfills. Furthermore, as landfills typically produce leachate for several hundred years after closing operations, WTE via HTC can make the management of leachate more sustainable in the long-term by avoiding or reducing it in the first place.

Lastly, the associated problems of foul-smelling and toxic gas emissions, water and soil pollution caused by the leachate, risks of explosion and fire hazards, and contribution to global warming can be avoided. Approximately 1.2 billion m^3 (**Fig. 5.3c**) of landfill gas from the landfilled MSW will be produced in the long-term. It is necessary to avoid further increases by quickly adopting a solution to Zimbabwe's solid waste disposal problems.

The stochastic WBM methodology for estimating leachate volumes avoids the limitations of most empirical models, fundamentally flawed by their deterministic nature. Most of the data required in WBM is stochastic or poorly defined (temperature, heat index, precipitation, runoff coefficients). Therefore, the use of deterministic models and techniques must be treated with caution.

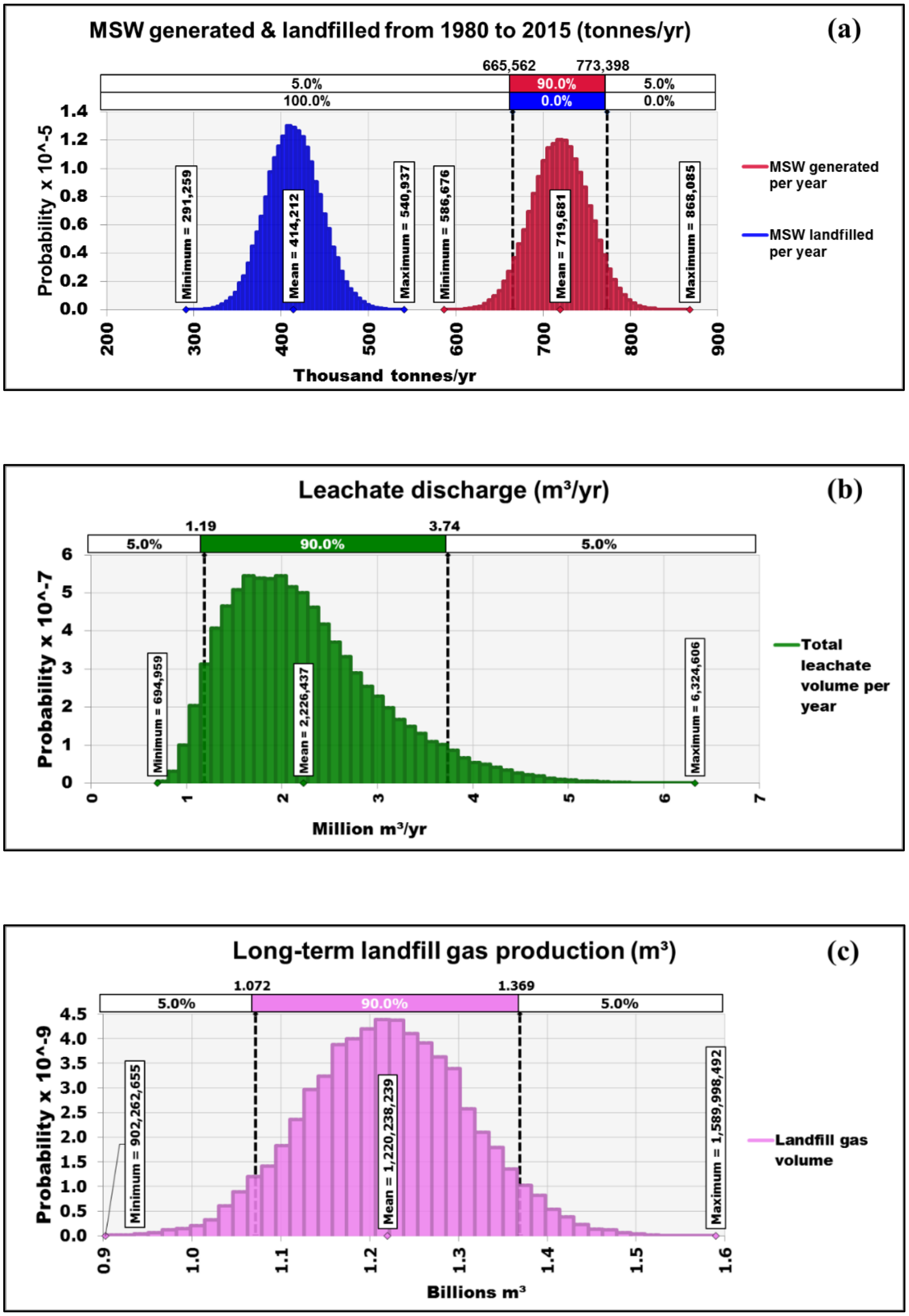


Fig. 5.3 Distribution probability of a) average generated and landfilled MSW b) leachate volume c) landfill gas production

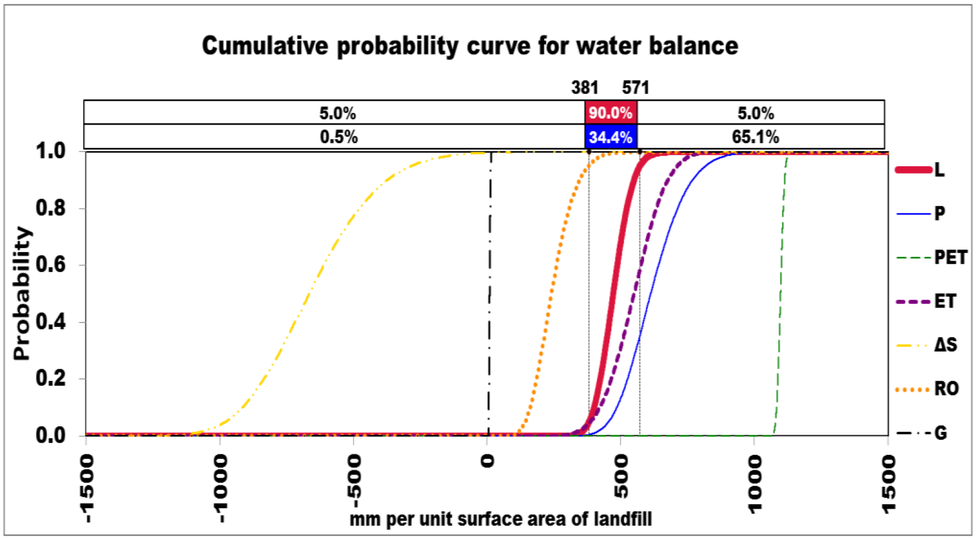


Fig. 5.4 Cumulative probability distribution for annual water balance

5.4 Conclusion

Using Monte Carlo simulations, 13 - 16 million Mg of MSW have been landfilled since 1980. At a 90% confidence interval, the leachate discharged from landfills is 1.19- 3.74 million m^3/yr or about 41 – 128 million m^3 in total since 1980. By introducing HTC as an WTE option, the landfill waste is reduced, as is the resulting leachate and methane. Roughly 2.23 million m^3/yr of leachate can be avoided by averting waste to HTC. Another added benefit is the reduction in the lethal concoction of chemicals that a typical landfill leachate harbors which would no longer contaminate groundwater sources. It is necessary to stress that this article is an initial approximation. This study could be used in the preliminary design of leachate control systems or to assess the impact of leachate on the environment. There is limited field data on the characteristics of landfill leachate in Zimbabwe, therefore, gathering of such data is highly recommended for future work.

Chapter 6: Comparative global warming potential assessment of BSG for coal-alternative fuel production and food

Chapter 6 focuses on the impact of BSG derived fuel relative to using BSG for flour production in terms of global warming potential. Unlike other feedstocks BSG can be used directly for food production. Scenarios for the other disposal methods, landfilling and feeding to animals are also modelled to see where HTC would stand if implemented.

6.0 Introduction

The prospect of extracting economic and environmental value from BSG via thermal conversion processes such as gasification [212, 213], pyrolysis [58, 214-216], hydrothermal carbonization (HTC) [217] has been studied. The treatment of BSG is overwhelmingly expensive and given its 70 — 90% moisture content [218], energy recovery via HTC is more appropriate. HTC involves the concurrent dehydration, polymerization (aromatization) and decarboxylation of biomass to increase its carbon content with the overall aim to raise its calorific value. This is realized by supplying saturated steam to a reactor to achieve operating conditions of 180 — 220°C under saturated pressure (20 -25 bar) for several hours (1 to 72 hours depending on the feedstock) [27]. The final solid product, hydrochar or biochar, is a lignite-like, easy to handle fuel with homogenous properties [14]. Direct combustion of BSG is not favorable as pre-treatment (drying) is required which consumes energy and raises costs. Drying, however, is necessary to prevent microbial degradation and chemical deterioration which occurs rapidly [219]. Drying in direct rotary-drum driers typically consumes a lot of energy [220] hence BSG is pressed and dried to a moisture content of 10% in most breweries [221]. BSG use as cattle feed is hampered by its insufficient degradation in rumen [222]. The application of HTC on BSG has been shown to yield an aqueous stream rich in macromolecular dissolved organic matter that can be a precursor for valuable chemicals [222]

Sub-Saharan Africa (SSA) still suffers from a serious electricity lag with roughly 633 million people living without access [3]. Roughly 80% of those deprived of electricity live in rural areas [4]. Reliance on wood-based biomass energy (fuel wood and charcoal) for cooking is higher in SSA, at 792 million people, than any other region [3, 5]. The use of traditional biomass along with its unsustainable harvesting and inefficient use is a gross mismanagement of natural resources. Despite the resounding reliance on bioenergy in Africa, the planning, management, production, distribution and use of biomass, hardly receives commensurate attention at national policy agendas. A possible approach to energy sustainability, is the modernization of the bioenergy sector. The rationale for engagement and development in this sector are threefold; mitigation of climate change and greenhouse gas (GHG) emissions, poverty alleviation and economic development and energy security improvement. The provision of clean and affordable energy is central to addressing the issue of global warming. Africa is reeling from the adverse effects of climate change. Variable rainfall patterns and low water availability have negatively impacted agricultural output. Herein lies another potential benefit of BSG, due to its nutritional and functional properties, it is increasingly being considered as an adjunct for human consumption. The fortification of biscuits [111-114], pasta [115, 116] and other bakery products and snacks has been investigated [117]. The potential health benefits in BSG are derived from its fiber (e.g. AX, β-glucans) and phenolic (e.g. hydroxycinnamic acid) components. The essential amino acid, lysine, is found in relatively high quantities in BSG compared to other cereal products [117]. Adding 10% of BSG to a bread formulation, for example, leads to a protein content increase of up to 50%, a fiber content increase of 10% and an essential amino acid content increase of 10% compared with conventional breads without BSG [223, 224]. BSG is dried and often milled before incorporating it into food. There are 15 minerals identified in BSG with the most abundant being calcium, sodium, potassium, magnesium and phosphorus [225]. Calcium reduces the risks of osteoporosis and colon cancer [226]. Magnesium protects against obesity [227] and Type 2 diabetes mellitus [228]. BSG contains 11% lipids in the form of triglycerides and free fatty acids. Fatty acids present in relatively large amounts in BSG are linoleic, oleic acids (unsaturated fatty acids), palmitic and small amounts of stearic acid (saturated fatty acids) [229]. These acids including phytosterol protect against conditions like high blood cholesterol levels or cancer [230]. BSG use in food production can alleviate the problems associated with seasonal food shortages and nutritional deficiency diseases which are still a major concern in Africa.

The main objective of this study is the evaluation and comparison of the environmental impact of two alternative uses for BSG, namely its use as a biofuel (by converting BSG via HTC into hydrochar) and as a source of flour for fortifying foods. The objectives of the study are to determine the following aspects: the quantification of BSG generated at the African level, the biocoal yield, its energy content and the potential quantity of BSG flour that can be produced. These parameters are estimated up to 2040 since data or projections on BSG generation are limited. Investigation on the variability of this potential feedstock over the 20-year period is important because (i) bioconversion plants, mills or other downstream processes need a predictable and reliable supply of feedstock over several years in order to justify capital investments (ii) it enables the quantification of the feedstock supply risk [231]. The outcome of this research serves to inform decision-making for policymakers, food security planning, investors and energy planners by uncovering opportunities lying in brewery waste. There are limited studies on the availability and energy potential of BSG in Africa. Biochar production via HTC has gained substantial attention, but few studies have investigated the potential of HTC biochar to address the challenges in Africa.

6.1 Materials and Methods

6.1.1 Current BSG availability, biochar and energy potential

BSG availability, biochar and energy potential in Africa was modelled in MS-Excel equipped with Palisade's @RISK add-in software for running Monte Carlo simulations [200]. For consistency in the assessments, historical beer production (1961-2013) data was taken from Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) for each country. This data was analyzed using @ RISK's distribution fitting function. This function selects from among several different continuous probability distributions, the one that best matches the historical production data. @RISK then ranks all the fitted distributions using one or more fit statistics. These include the Bayesian Information Criteria (BIC), Anderson-Darling (AD), the Chi-Squared, Kolmogorov-Smirnov (K-S), and Root-Mean Squared Error (RMSErr). The Akaike Information Criterion (AIC) statistic was used to measure the goodness-of-fit with the smaller value representing the better fit. The best fitting models were inputted into the equation (1) below. BSG moisture content is variable, ranging from 70 — 90% [232], and the simplest approach was to assume a uniform distribution. The uniform distribution is preferable when the only information available about some random variable is its limits. All the values within the limits are equally likely. This distribution is useful when very little information is available, but it is thought that the variability of the corresponding phenomenon is still an important feature to model. The probability distribution function for BSG water content was inputted into equation 1 in order to calculate the BSG quantities on a dry basis. The mathematical formulation of the expected biocoal yields and energy potential are shown in equations (1) to (2). Finally, Monte Carlo simulations were run for 50,000 iterations with Median Latin Hypercube sampling.

$$P_{iBC} = A_{iB} \times R \times Y_{BSG} \times (1 - m) \qquad (6.1)$$

Pi_{BC} is the biocoal yield derived from BSG in Mg/yr, A_{iB} is the probability distribution function for annual beer production in Mg/yr for country *i*, *R* is uniform distribution for ratio of wet BSG to beer and Y_{BSG} is a uniform distribution for the percentage yield of biocoal from hydrothermally converted BSG and *m* is the uniform distribution for BSG moisture content. Drawing upon extant literature, 14 — 20 kg of wet BSG are produced per 100 L of finished product beer [117, 233]. Biocoal yields are reported to range between 47.5 — 51.1% and calorific values based on available experimental literature for BSG-derived biocoal range between 29.6 — 31.8 MJ/kg [217, 234].

$$E_{BC} = P_{iBC} \times H_v \qquad (6.2)$$

E_{BC} energy content of biocoal in GJ and H_U is the uniform distribution function for the calorific value of BSG-derived biocoal.

6.1.2 Estimation of yield of BSG flour

Depending on the particle size, products of conventional milling are categorized either as flour, shorts, or bran [235]. Bran can be further classified into coarse and fine bran. In this study the term flour will include the flour, fine bran and shorts, all included in the umbrella term BSG flour (BSGF). From experimental studies conducted by [236] the yield of BSGF from milled BSG that can be expected in commercial practice is between 74.7 — 82.7%. From a Dreese and Hoseney [237] patent which describes the removal of mainly the hull from BSG to produce flour, a yield of 51% is reported with a 22% portion containing a mixture of bran and inedible hulls. With such a variation, a uniform distribution ranging from 50 — 80% BSGF yield was assumed in this study. The yield depends on the initial moisture content of BSG, the presence or absence of yeast and milling procedure.

6.2 Projected BSG availability, biochar and energy potential in 2040

6.2.1 Stochastic Time Series forecast

A stochastic time series forecast was performed on MS-Excel to project annual beer production for each country using @Risk's time series function. Since predictions of time series values are inherently uncertain, @RISK accounts for the uncertainty by observing the whole range of possible time series projections in a model. The function selects the best fitting model from 17 statistical time series models, including ARMA (autoregressive, moving average) processes, GBM (geometric Brownian motion) and its variations, and ARCH (autoregressive conditional heteroskedasticity). Fitting times series processes to the historical data using @RISK involves (i) defining the input data, (ii) specifying the time series processes to fit (iii) running the fit and interpreting the results [200]. For each country, projected beer production was inputted into equation 1 (A_{iB}).

6.2.2 Forecasting BSG generation in Africa using economic and demographic variables

An entirely different methodology was used to validate the stochastic time series projections. A multiple linear regression model using gross domestic product (GDP) and population size as selected variables was deemed most relevant for Africa's BSG generation. It is widely accepted that waste generation rates are strongly correlated to population size and GDP so a separate model was developed to forecast BSG generation in 2040. From its production to consumption, beer has a long supply chain and accounts for a significant contribution to the GDP. In 2009, for example, an estimated R94.2 billion (or 4.4%) of South Africa's (GDP) came from the beer and liquor industry [238]. There is a strong relationship between GDP and beer production hence our choice of this variable. With a greater population, a higher rate of BSG generation can be expected. South Africa, for example, has one of the highest per capita beer consumption rates in the world, and it is continuing to rise [239]. First, we assumed mean BSG generation rate (Y) is related to the predictor variables X1(GDP) and X2 (Population size) in a multiple linear regression model such that:

$$y = k_1 {x^a}_1 + k_2 {x^b}_2 \qquad (6.3)$$

Current GDP and population data for each country was retrieved from the [240] and the mean country BSG generation rate obtained from our calculations. The data was fitted in MS-Excel. The parameters for our model (constants a, b, k_1 and k_2) were obtained by linear or nonlinear regression using the software. Once we found the value for the constants, we were able to predict BSG generation rates using GDP forecast data for the year 2040 from [240, 241].

6.3 Approach and assumptions about global warming potentials and timescales

The environmental footprint of HTC and flour production from BSG was examined by means of the Global Warming Potential or GWP (25 years) impact category. This impact category was chosen since it represents the most significant environmental issues within the energy and food production sector. South Africa was chosen as the case study because of the availability of data on emission factors from that country and also since it is the number one producer of beer in Africa [242], it stands to benefit most from either of these two strategies. All environmental impacts engendered from the production of a product prior to becoming a waste were neglected. A zero burden was assumed for all process leading up to BSG generation. The performance analyses for all scenarios were carried out up to 2040. In this study, GWP assessment of BSG usage was considered under 4 scenarios. The system boundaries of all scenarios considered are shown in **Fig. 6.1** respectively.

Scenario 1: BSGH - In this scenario, BSG is converted to hydrochar (BSGH). The HTC plant is assumed to be located near Alrode Brewery as it is the largest brewery in South Africa [243]. The rest of the BSG will be hauled to and processed in this plant. According to [244], economy-of-scales typically favor large infrequent HTC plants compared to small decentralized ones for a given wide coverage area despite the increase in feedstock costs due to longer haulage distances.

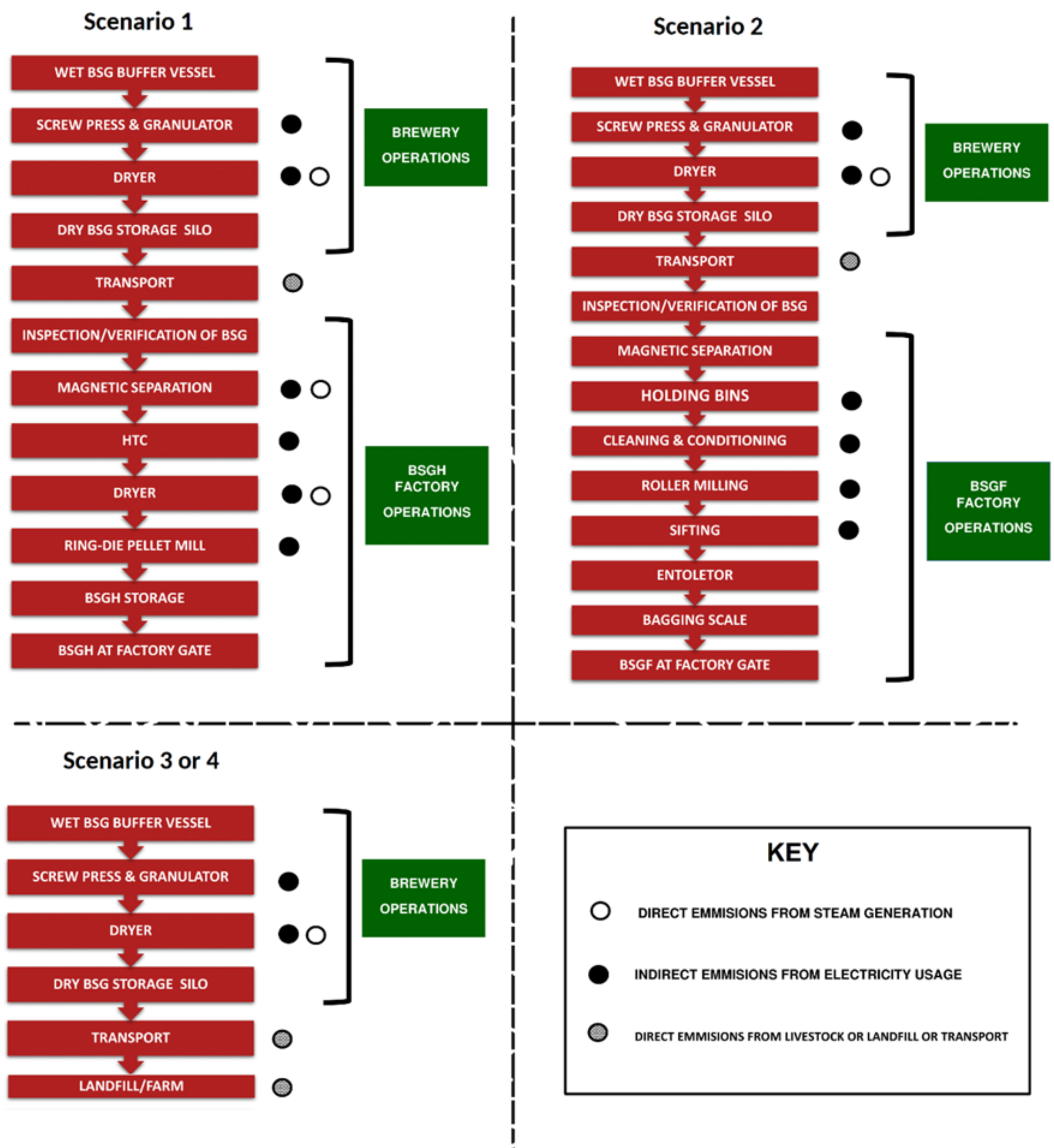


Fig 6.1. Scenarios for BSG usage

BSGH is envisaged for electricity production, however, the analysis here is up to the factory gate. Wet BSG (with an assumed moisture content of 80%) is heavy to transport, and it is likely to drip while being hauled. In a wet state it would take two or three days for biological degradation to take place [245]. As shown in **Fig 6.1**, wet BSG from the brewery outlet is temporarily stored in a buffer vessel to compensate for fluctuations in production and then a screw press and granulator are used to dewater the BSG to 67 % w/w dry matter [224]. Although HTC can handle wet feed, the BSG is further steam dried to a moisture content of 10% to lower transport costs. Superheated steam drying (200 - 240 °C) for steam temperature of BSG in a rotary dryer offers increased efficiency, reduced risk of fire and explosion, deodorization, faster drying rates, sterilization and significant reductions of stickiness of BSG to the drum [246]. Assuming a 42% moisture content for BSG and drying to 10% moisture content, the energy per kg of water removed is 0.65 MJ/kg [246]. The main stages of BSGF processing in order of sequence are pre-inspection, magnetic separation, HTC, drying and pelletization. An in-depth look at what the HTC plant and processing involves is given by [247]. Emissions from HTC were estimated from the coal quantity burned in the boiler to produce the steam required for the process. A Circulating Fluidized-bed Combustion boiler (CFBC) with an efficiency of 83% was assumed. The combustion temperature of a CFBC boiler varies from 800ºC to 900ºC resulting in significantly reduced NOx formation compared to pulverized coal combustion which operates at higher temperature of up to 1700 °C [248]. The properties of coal and water requirements are shown in **Table 6.2**. Coal quantity required was estimated by multiplying the mass of steam required by the enthalpy difference of steam and water and dividing by the product of the boiler efficiency and gross calorific value of coal. Estimates of emissions from coal usage (CO_2 and CH_4 emissions) were based on emission factors and South African coal ultimate composition as shown in equations and details given by [247]. In addition to biochar, HTC further produces a liquid phase [249]. Using BSG as feedstock this process water was found to contain mainly the following compounds; lactic, formic, acetic, levulinic, and propionic acid and 5-hydroxymethylfurfural. Recirculation of the process water was suggested to reduce the organic load of process water before discharging [250]. These compounds and others in trace amounts collectively form the dissolved organic matter in the liquid phase [222]. The authors would like to point out that the model presented here cannot fully capture all parameters. There is not enough literature on the treatment of this liquid phase. Emissions from the treatment of this process wastewater were ignored.

Scenario 2: BSGF - BSG is dried and milled into BSGF. The process is similar to scenario 1 up to the BSGF factory. BSG haulage operations would be the same for both scenarios 1 and 2. One BSGF plant is assumed to process all the BSG. Since [237] recommend BSG to be dried to less than about 15%, and preferably about 9%, before milling, our 10 % moisture content before hauling is reasonable. **Fig. 6.1** shows the process steps in producing the final product and important parameters and assumptions are shown in **Table 6.2**.

Table 6.1 Capacity of South Africa breweries

Brewery[a]	Capacity (million hl)[b]	Location	BSG generation (% of total)[c]	Distance from BSG-HTC/BSGF plant (km) by road or rail[d]
Alrode	8.3	Johannesburg, Gauteng	26.4	20[e]
Chamdor	2.2	Krugersdorp, Gauteng	7.0	60
	2.4	Port Elizabeth, Eastern Cape	7.6	1073
Newlands	4.5	Cape Town, Western Cape	14.3	1407
Polokwane	1.5	Polokwane, Limpopo	4.8	337
Prospecton	5.3	Durban, Kwazulu Natal	16.9	562
Rosslyn	7.2	Rosslyn, Gauteng	22.9	113

a - [251]

b - [252]

c – Assumption that BSG generation is directly proportional to plant capacity

d – Using brewery locations from SAB website and Google maps. Distances shown are for a one way trip. Distances over 60km are covered by rail.

e - Assumption

The basic operations in BSG milling are receiving, inspection and storage, cleaning and conditioning, milling and product packaging. The factory receives a rail or truck delivery of BSG and from the receiving pits the BSG is conveyed over a magnetic separator to remove metallic foreign matter. Cleaning removes any coarse impurities using differences in size or shape and conditioning ensures an optimum and uniform moisture content that improves separation when milling. Milling is a combination of initial breaking using break rolls followed by sieving and reduction (to produce finer particles) [253]. The product from each sifter is classified into a specific mill stream such as bran, flour or shorts. An entoleter is used to disinfect milled BSGF. BSG is fed into a rotor revolving at a high speed and flung outward onto studs on the walls of the machine upon which insects are broken on impact and separated from the bulk [254].

Table 6.2 Assumptions for scenario analysis

Scenario	Parameter	Value	Reference
1	Solid (dry BSG) to water ratio	1: 10	[255]
	Carbon footprint of potable water	0.137 kg CO_2/m^3	[256]
	HTC reactor steam temperature and pressure	200°C 1.5 MPa	[255]
	Specific enthalpy of saturated steam at reactor conditions	2792 kJ/kg	Steam Tables
	Boiler feedwater enthalpy	1087 kJ/kg	
	Gross calorific value of South Africa coal	27 MJ/kg	[257]
	Ultimate analysis of South Africa coal	C (70.8%), H (4.49%), N (1.61%), O (23.1%), S (1.4%)	[257]
	Life-cycle GHG emissions for coal-fired electricity in South Africa	1.06 tCO_2 /MWh	[258]
	electricity consumption for pelletization of HTC treated biomass	17 kWh/ton	[259]
1 - 4	CO_2-emission factor for average freight truck	161.8 g per short ton-mile	[260]
	CO_2-emission from rail transport operations	22 g per tonne-km	[261]
	Specific energy consumption of a screw press	10–30 kWh/tonne. Assume 20kWh/tonne	[262]
	Low-intensity magnetic separators electricity consumption	1.2 kwh of energy per ton	[263]
1 - 4	Frequency of BSG Removal from Brewery Site	3 times a week	[264]

		(Large breweries 2 to 3 times a week)	
2	Specific power consumption of individual grinding rolls Emission factor for milling of dried distillers' grain Specific power consumption of entoletor Specific power consumption of cleaning and conditioning	4.955 to 24.26 kWh/t Assume 14.6 kWh/t 2.3 kg $CO_{2\text{-eq}}$ kg $^{-1}$ feed input. Assume same for BSG Assume 7.3 kWh/t based on carbon footprint of milling being double that of entoleters when milling wheat Assume 3.7 kWh/t based on carbon footprint of cleaning being roughly 25% of the footprint of milling wheat	[265] [266] [267] [267]
3	BSG maximum biogas potential Exploitable potential Global Warming Potential over 20-year time horizon	120 NL/kg fresh matter (60%v methane, 40% carbon dioxide) Up to 20% when pretreated. Assume 10 % in our study for landfill without pre-treatment of BSG 1 for CO_2 56 for CH_4	[268] [268] [269]

Scenario 3: LANDFILL - BSG is collected and sent to a landfill. BSG usually degrades slowly under anaerobic conditions since it is a lignocellulosic material [270]. In this scenario each brewery will send BSG to the nearest landfill, assumed to be 20 km away by road. BSG is simply pressed up to 42 % w/w dry matter to reduce transport costs [245].

Scenario 4: FEED – BSG is collected and transported to nearby farms to be used as feed. Farms are assumed to be 20km from each brewery by road. BSG is pressed up to 42 % w/w and it is stable enough for use by farmers [245]. Methane generation from feed consumption varies depending on the breed, species, digestibility of the animals, the level of feed intake and other activities [271]. For simplicity it was assumed BSG would feed cows only. According to [245], the fiber content of BSG is 150–160g/kg dry matter making it unsuitable for non-ruminant animals such as pork and poultry. The methane yield would be estimated as the fraction of the gross energy in BSG intake lost as energy through methane generation [272]. Roughly an 8.4% to 10% methane conversion rate (% of methane energy loss per gross energy intake) can be expected in beef cattle [273]. 1 kg methane has an energy content of 55.65 MJ. A mid value 9.2% methane conversion rate was assumed in this study. The gross energy is 21.4 MJ/kg [274].

6.4 Results and Discussion

6.4.1 BSG generation in Africa

Historical trends in BSG generation are shown in **Fig 5.2a**. Between 1961 and 2013, cumulative BSG generation in Africa amounted to 12.9 million Mg (dry basis) on average. An estimate in the range of 10.6 — 15.2 million Mg at a 90% confidence level is suggested. Almost half of this 5.9 million Mg was produced between 2000 and 2013. For the period 1961 to 2013, BSG generation stood at 34,500 — 551,400 Mg/yr. Roughly 207,000 Mg/yr was generated on average. At a 90% confidence level about 47,600 — 436,000 Mg/yr are generated.

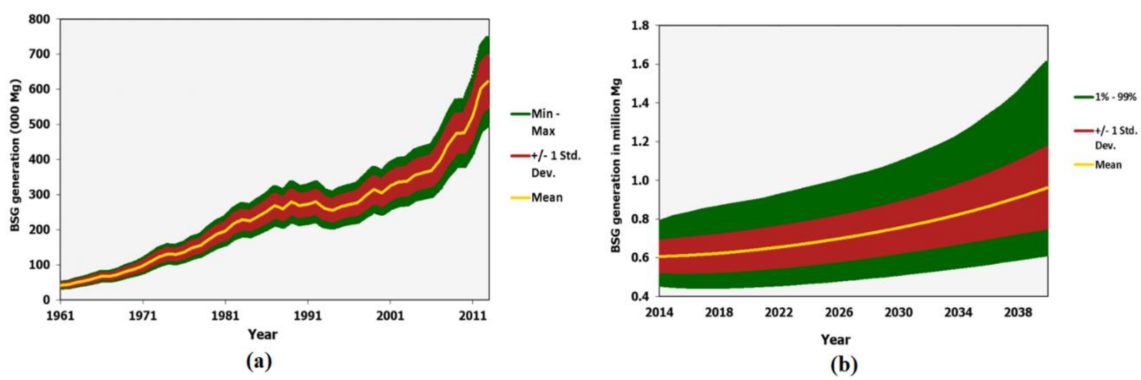


Fig 5.2 a) Total dry BSG generation in Africa by year from 1961 to 2013 (Mg) b) Projected total dry BSG generation in Africa by year from 2014 to 2040 (Mg)

BSG generation at an African level, increased from a mean of 41,000 Mg in 1961 to 627,000 Mg in 2013, a compound annual growth rate (CAGR) of 5.38 %. For comparison, the African beer market was quoted as having a CAGR of 7.7% from 2008 to 2013 in terms of total production [275]. BSG generation prognosis for the period from 2014 to 2040 is presented in **Fig. 5.2b**. The red area represents an estimate of BSG amounts within 1 standard deviation of the mean and the green area gives the 99% forecast band. It can be observed that the band widens as we move to either side of the mean. This is because variance of the predictions increases the further new predictions for BSG generation rate lie from the mean of the sample values. In 2020, BSG generation (on a dry basis) in Africa is estimated to lie in the range of 0.51 —0.91 million Mg/yr at a 90 % confidence level and 698,000 Mg/yr on average. **Fig. 6.3** shows mean BSG generation rate by country for 2020 and 2040. South Africa alone accounts for 28% of African BSG generation and 15 % is from Nigeria in 2020.

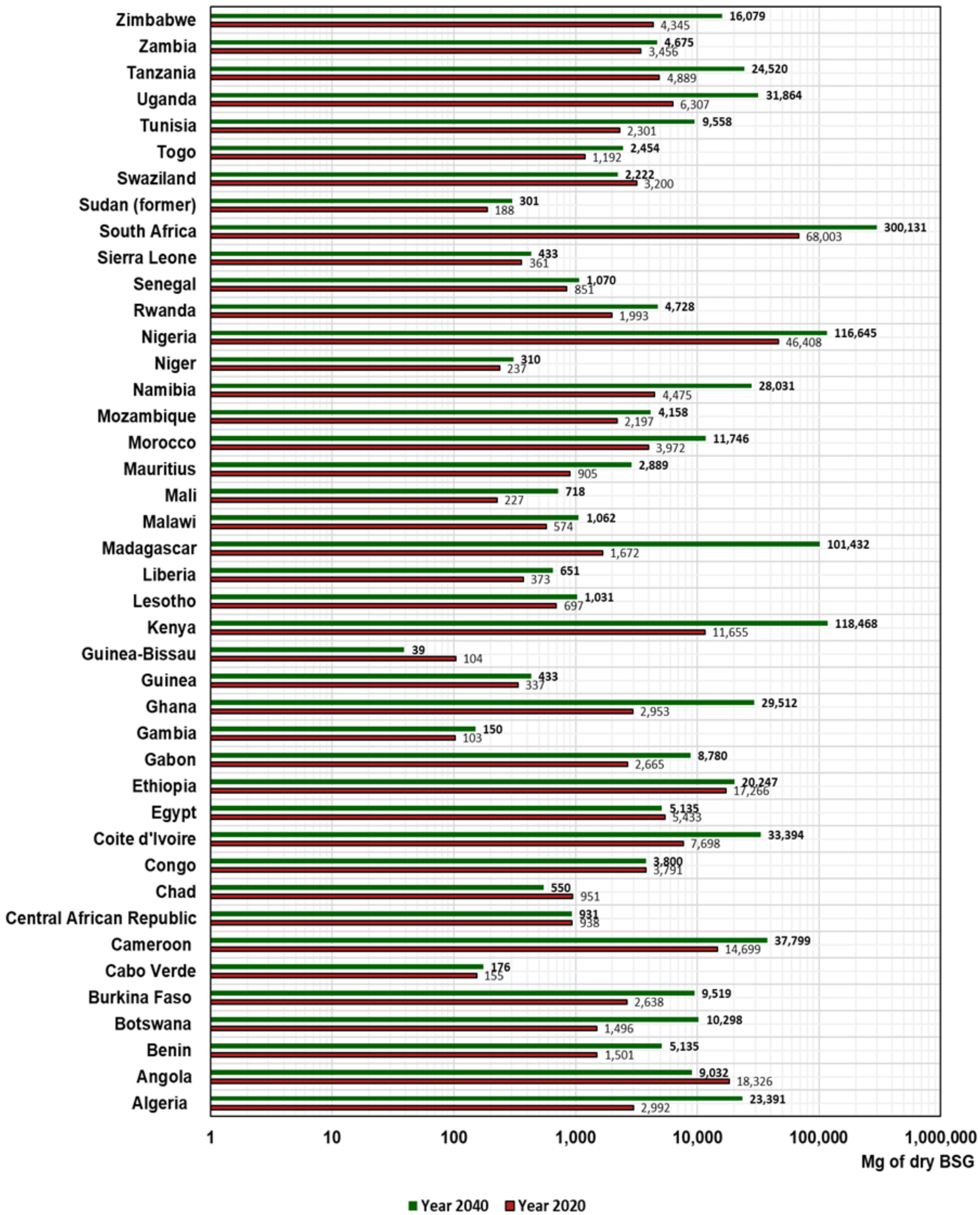


Fig. 6.3 Current and projected mean BSG generation rate (Mg) on a dry basis in African countries

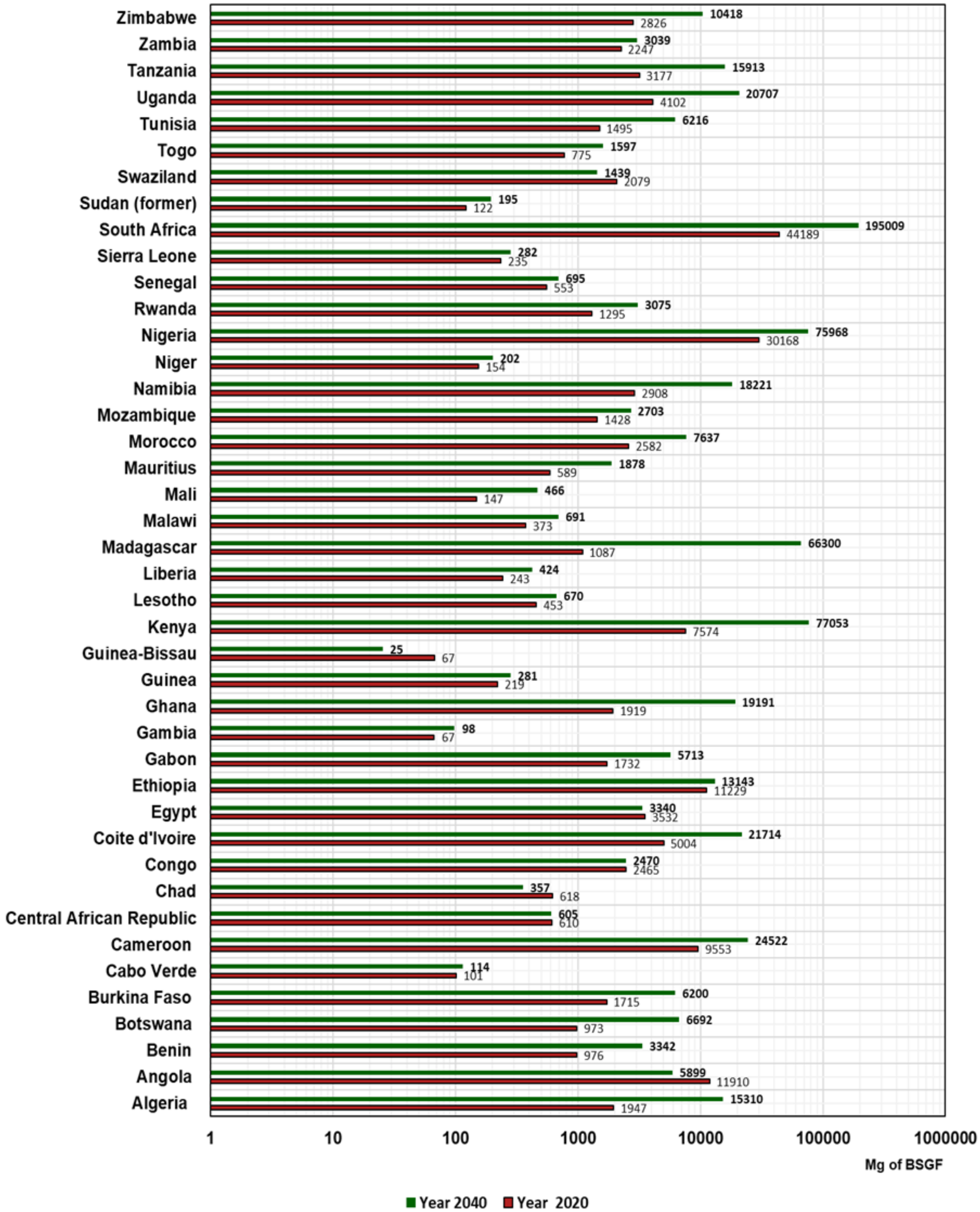


Fig. 6.4 Current and projected mean BSGF production rate (Mg) on a dry basis in African countries

Table 6.3 BSG generation and selected distribution model

Country	Current dry BSG generation (Mg/yr)			Dry BSG generation in 2040 (Mg/yr)		
	Min	Max	Best fit distribution model	Min	Max	Time Series Forecast Model*
Algeria	1,364	17,911	Gamma	616	518,434	MA
Angola	500	53,801	Triangle	69	323,940	AR
Benin	170	15,145	Exponential	280	58,133	ARMA
Botswana	172	4,133	Triangle	3,285	28,781	MA
Burkina Faso	180	7,528	Triangle	243	155,273	ARMA
Cabo Verde	0	464	Triangle	15	2,182	MA
Cameroon	1,104	41,733	Triangle	999	712,541	ARMA
Central African Republic	250	2,011	Triangle	170	3,777	ARMA
Chad	0	2,849	Triangle	440	660	MA
Congo	100	11,148	Triangle	3,040	4,560	ARMA
Coite d'Ivoire	354	22,311	Kumaraswamy	3,031	102,551	MA
Egypt	800	14,647	Triangle	312	55,918	ARMA
Ethiopia	4,050	43,670	Triangle	1,397	199,521	ARMA
Gabon	27	5,303	Uniform	349	120,494	ARMA
Gambia	0	307	Triangle	19	814	MA
Ghana	154	6,851	Triangle	490	892,232	MA
Guinea	32	2,201	Gamma	10	12,376	AR
Guinea-Bissau	0	311	Triangle	1	545	MA
Kenya	2,138	30,623	Triangle	4,176	1,423,636	MA
Lesotho	0	2,087	Triangle	262	3,315	MA
Liberia	0	1,115	Triangle	51	4,745	ARMA
Madagascar	15	20,741	Exponential	705	2,156,627	MA
Malawi	0	1,717	Triangle	186	4,931	ARMA
Mali	0	677	Triangle	331	1,533	ARMA
Mauritius	93	1,717	Uniform	894	5,424	MA
Morocco	813	7,627	Triangle	1,251	94,902	MA
Mozambique	306	21,742	Exponential	73	86,442	ARMA
Namibia	0	13,371	Triangle	12,411	47,678	MA
Niger	0	709	Triangle	61	1,497	ARMA
Nigeria	1,201	136,619	Triangle	23,125	478,084	ARMA
Rwanda	0	5,954	Triangle	774	27,317	ARMA
Senegal	284	1,417	Uniform	228	5,306	ARMA
Sierra Leone	1	929	Triangle	65	2,253	ARMA
South Africa	7,501	128,506	Uniform	104,570	648,033	MA
Sudan (former)	0	560	Triangle	5	6,761	ARMA
Swaziland	0	9,560	Triangle	63	48,366	MA
Togo	3	2,380	Uniform	181	21,237	ARMA
Tunisia	1,261	5,968	Weibull	1,709	51,084	MA
Uganda	300	18,247	Triangle	2,256	126,172	MA
Tanzania	245	57,198	Exponential	2,300	224,446	ARMA
Zambia	235	7,123	Triangle	930	20,308	ARMA
Zimbabwe	577	43,314	Exponential	91	757,052	BMMR

* Forecast of annual beer production to 2040

Autoregressive-AR, Autoregressive-Moving Average -ARMA, Brownian Motion Mean Reversion-BMMR

Table 6.4 Estimation of BSGH and its energy content

Country	Potential Biochar production (Mg/yr)				Potential Energy Content (GJ/yr)				% energy contribution*
	Min.	Max.	Mean	Std Dev.	Min	Max	Mean	Std. Dev	
Algeria	649	9,119	1,475	723	18,938	268,117	44,984	22,104	0.013
Angola	242	27,271	9,035	6,218	7,205	856,482	275,540	189,879	0.251
Benin	81	7,513	740	657	2,377	227,066	22,582	20,060	0.253
Botswana	82	2,084	738	462	2,406	65,917	22,499	14,114	0.082
Burkina Faso	85	3,780	1,300	857	2,554	118,373	39,656	26,177	0.249
Cabo Verde	0	236	76	54	0	7,381	2,328	1,649	0.060
Cameroon	530	21,105	7,247	4,742	15,574	673,752	221,027	144,845	0.461
Central African Republic	121	1,015	463	191	3,676	32,135	14,109	5,833	0.435
Chad	0	1,428	469	332	0	45,116	14,298	10,129	0.855
Congo	48	5,639	1,869	1,288	1,404	177,770	57,016	39,353	0.163
Coite d'Ivoire	169	11,272	3,795	2,561	4,965	357,273	115,761	78,256	0.223
Egypt	382	7,372	2,679	1,617	11,122	233,445	81,700	49,383	0.006
Ethiopia	1,934	22,152	8,513	4,613	56,548	698,371	259,628	140,948	0.318
Gabon	13	2,706	1,314	751	387	86,345	40,073	22,966	0.126
Gambia	0	155	51	36	0	4,879	1,544	1,094	0.066
Ghana	76	3,498	1,456	705	2,296	110,041	44,397	21,557	0.040
Guinea	15	1,111	166	119	446	35,144	5,065	3,645	0.088
Guinea-Bissau	0	155	51	36	0	4,886	1,559	1,104	0.093
Kenya	1,016	15,433	5,746	3,321	30,146	489,848	175,242	101,447	0.187
Lesotho	0	1,055	343	243	0	32,909	10,473	7,418	0.195
Liberia	0	566	184	0	0	17,955	5,608	0	0.122
Madagascar	7	10,042	824	817	211	303,802	25,146	24,943	0.576
Malawi	0	868	283	200	0	27,662	8,636	6,119	0.082
Mali	0	342	112	79	0	10,857	3,410	2,416	0.045
Mauritius	45	876	446	231	1,308	27,848	13,615	7,073	0.035
Morocco	395	3,885	1,958	696	12,064	121,679	59,732	21,290	0.015
Mozambique	146	10,885	1,083	933	4,297	348,117	33,034	28,469	0.141
Namibia	0	6,791	2,206	1,561	1	213,475	67,294	47,677	0.288
Niger	0	359	117	83	0	11,445	3,569	2,529	0.032
Nigeria	581	69,380	22,882	15,775	17,173	2,188,141	697,864	481,694	0.169
Rwanda	0	2,999	983	695	1	93,684	29,970	21,234	0.620
Senegal	135	723	419	162	3,976	23,072	12,794	4,943	0.022
Sierra Leone	1	468	178	101	23	14,700	5,425	3,082	0.087
South Africa	3,588	65,573	33,526	17,241	105,606	2,075,718	1,022,665	527,086	0.036
Sudan (former)	0	285	93	65	0	8,958	2,822	2,000	0.003
Swaziland	0	4,851	1,578	1,116	1	153,850	48,121	34,100	0.810
Togo	1	1,215	587	339	40	38,641	17,918	10,347	0.112
Tunisia	599	3,010	1,135	547	17,421	95,927	34,604	16,712	0.027
Uganda	144	9,299	3,110	2,096	4,193	291,844	94,834	63,993	0.380
Tanzania	118	27,499	2,410	2,291	3,454	810,677	73,497	69,891	0.488
Zambia	113	3,606	1,704	702	3,607	112,666	51,973	21,476	0.065
Zimbabwe	276	21,430	2,142	1,858	8,042	667,606	65,343	56,728	0.408

*** Total BSGH energy content/total primary energy**

Table 6.5 Projections of BSGH quantities and energy content in 2040

Country	Potential Biochar production (Mg/yr)				Potential Energy Content (GJ/yr)			
	Min.	Max.	Mean	Std Dev.	Min	Max	Mean	Std. Dev
Algeria	305	263,129	11,531	10,805	9,102	7,915,450	351,657	329,735
Angola	35	161,121	4,453	6,885	1,071	5,093,250	135,791	210,065
Benin	139	29,245	2,532	1,775	4,062	894,810	77,233	54,208
Botswana	1,614	14,295	5,077	1,434	47,769	448,578	154,846	43,987
Burkina Faso	117	75,478	4,693	4,276	3,638	2,210,054	143,135	130,572
Cabo Verde	7	1,112	87	56	212	34,500	2,641	1,713
Cameroon	476	351,041	18,636	14,652	14,934	10,880,428	568,331	446,950
Central African Republic	82	1,918	459	174	2,559	61,071	13,996	5,329
Chad	209	337	271	32	6,115	10,726	8,270	1,001
Congo	1,446	2,328	1,873	220	42,249	74,110	57,140	6,913
Coite d'Ivoire	1,457	50,209	16,462	5,889	43,397	1,592,841	502,134	180,372
Egypt	153	27,081	2,531	1,717	4,448	849,137	77,210	52,436
Ethiopia	686	98,508	9,982	6,549	20,869	2,942,716	304,458	200,044
Gabon	168	59,112	4,329	2,969	4,993	1,773,185	132,037	90,694
Gambia	9	415	74	35	278	12,355	2,261	1,063
Ghana	248	435,027	14,549	14,984	7,443	13,008,582	443,731	456,916
Guinea	5	5,929	213	214	159	189,055	6,509	6,544
Guinea-Bissau	1	263	19	15	21	8,103	587	457
Kenya	2,101	679,052	58,400	45,086	65,321	21,198,300	1,781,217	1,376,247
Lesotho	128	1,666	508	161	3,872	50,722	15,499	4,944
Liberia	25	2,356	321	25	753	73,559	9,786	753
Madagascar	357	1,064,578	50,013	58,596	10,469	33,327,258	1,525,916	1,790,586
Malawi	95	2,463	524	226	2,797	75,157	15,978	6,910
Mali	159	757	354	68	4,769	22,806	10,789	2,102
Mauritius	453	2,719	1,424	286	14,342	82,319	43,446	8,815
Morocco	608	45,576	5,790	3,230	18,540	1,430,387	176,632	98,763
Mozambique	36	42,847	2,050	1,948	1,137	1,261,236	62,509	59,421
Namibia	6,042	23,803	13,819	2,379	175,491	732,766	421,488	73,584
Niger	29	738	153	64	873	22,322	4,659	1,956
Nigeria	11,668	231,063	57,506	23,137	344,920	7,120,595	1,753,975	707,956
Rwanda	369	13,403	2,331	1,082	10,899	424,984	71,079	33,053
Senegal	111	2,589	527	208	3,392	76,789	16,083	6,350
Sierra Leone	32	1,150	213	102	992	36,481	6,511	3,120
South Africa	51,473	309,536	147,964	32,661	1,637,568	9,770,080	4,512,959	1,005,004
Sudan (former)	2	3,216	148	160	71	93,816	4,518	4,884
Swaziland	30	23,338	1,095	1,045	944	713,329	33,410	31,895
Togo	91	10,204	1,210	763	2,782	324,603	36,888	23,267
Tunisia	861	25,622	4,712	2,069	26,108	812,290	143,719	63,249
Uganda	1,133	60,143	15,708	5,879	34,639	1,904,245	479,099	179,939
Tanzania	1,159	113,224	12,088	7,396	35,287	3,324,378	368,736	226,068
Zambia	459	10,224	2,305	936	13,534	322,588	70,303	28,618
Zimbabwe	46	376,332	7,926	12,833	1,423	11,938,435	241,769	392,366

This is commensurate with beer production data. In 2017, for example, total beer production of Africa amounted to about 148 million hectoliters. Nigeria came in second as the leading beer producing African country with a volume of about 26 million hectoliters after South Africa at 32 million hectoliters [242]. As seen from **Fig. 6.2b** there is a 99% probability BSG generation in 2040 will be between 0.61 million Mg and 1.60 million Mg. South Africa is still expected to lead the region in 2040 at 300,131 Mg/yr of BSG (see **Fig. 6.3**) from 68,003 Mg in 2020. This represents a CAGR of 7.71 %. The best fitting probability distribution models for dry BSG generation as well as the range are presented in **Table 6.3**. On the same table, the time series model for projecting annual beer production is indicated.

6.4.2 Estimation of BSG-derived biochar and its energy potential

Africa can produce between 16,500 — 276,000 Mg of biochar annually from BSG via HTC. A mean production rate of 102,000 Mg is possible with an energy potential of 3.1 million GJ. In 2040, the amount of hydrochar that can be produced is 475,000 Mg with an energy content of 10.3-20.0 million GJ at a 90% confidence level. The amount of biochar that be produced is shown in **Table 6.4** for each country. The variation in values seen on a country-to-country basis is very large. It can be seen from the data presented in the **Table 6.4**, that BSG-derived biochar can contribute a small amount (0.20 % on average) to the current total primary energy consumption of each country. Whilst this figure is low, it should not by any means cast doubt on the HTC's potential to address Africa's energy problems. This study excluded other potential biochar feedstocks such as municipal solid waste, algae and water hyacinth, crop residues and agro-industrial wastes. HTC is an all-inclusive process for the thermochemical conversion of carbon feedstocks so low biomass quantities of one type of biomass can be processed with another type. Potential exists for in-plant conversion of BSG into biochar especially for leading beer producing African countries like South Africa and Nigeria and so may be worth exploring for breweries in those locations.

6.4.3 Model validation - comparison of stochastic forecast model with regression model

The equation relating the independent variables GDP and population size to BSG generation is given in **Table 6.6**. A graphical depiction of the plot is shown in **Fig. 6.5 a-b**. As seen in **Table 6.6**, BSG generation in Africa is mainly dependent on GDP and not on the population size. It is evident from the values of k_2 and b that the term involving x_2 is negligible such that we can state:

$$y = k_1 {x^a}_1 \qquad (6.4)$$

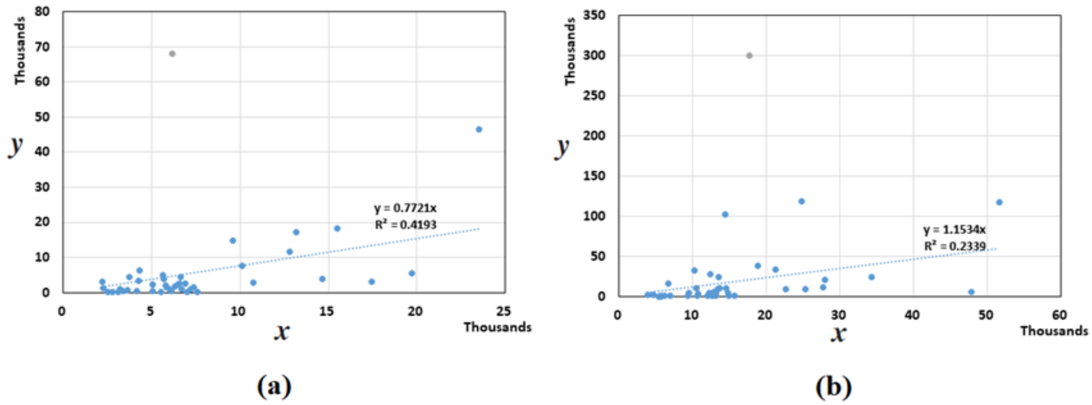


Fig. 6.5 Plot of (a) mean BSG generation rate (Y) in Mg/yr (Y) against a function of the current GDP and population (X) (b) Y against X in 2040

Table 6.6 Overview of BSG generation prediction model

Equation	$y = k_1 {x^a}_1 + k_2 {x^b}_2$
Optimized values of parameters of equations	k_1 = 0.7221, k_2 = 201.8323941263 a = 0.377695109, b = 0

Firstly, GDP per capita data was applied into the formula but there was no good correlation between the variables. In contrast when total GDP values were applied using the power law model, a satisfactory correlation was obtained. As GDP rises, we expect a rise in beer production and BSG generation. One study reports [276] that the relationship between income and beer consumption as an inverse U-shape with consumption initially rising with rising incomes eventually tapering off at higher levels of income. A similar trend can be expected for BSG generation. Despite the linearity of the relationship, a low correlation coefficient is expected due to uncertainty in the variables. By inputting forecasted values of GDP and population size in 2040 into equation 2, **Fig. 6.5b** was obtained. In this case the line of best fit suggests that k = 1.15. The forecasts made by the regression model are very comparable with the stochastic time series forecast. The parity plots show a relatively small scattering around the bisecting line. Although the regression model gives lower estimates for some countries, there is general agreement as most of the values fall within the range given by the stochastic model. This further demonstrates the superiority of stochastic models as they paint a wider picture.

6.4.4 BSG derived products and their global warming potentials for scenarios 1 to 4

The potential amount of flour that can be obtained in each country is represented in **Fig 6.4.** Using South Africa as a case study, **Fig 6.6** shows the future trends on BSG derived products (biocoal and flour). BSG, BSGF and BSGH production can be expected to increase at a CAGR of 2.20% from 2020 to 2040 as seen from the figure.

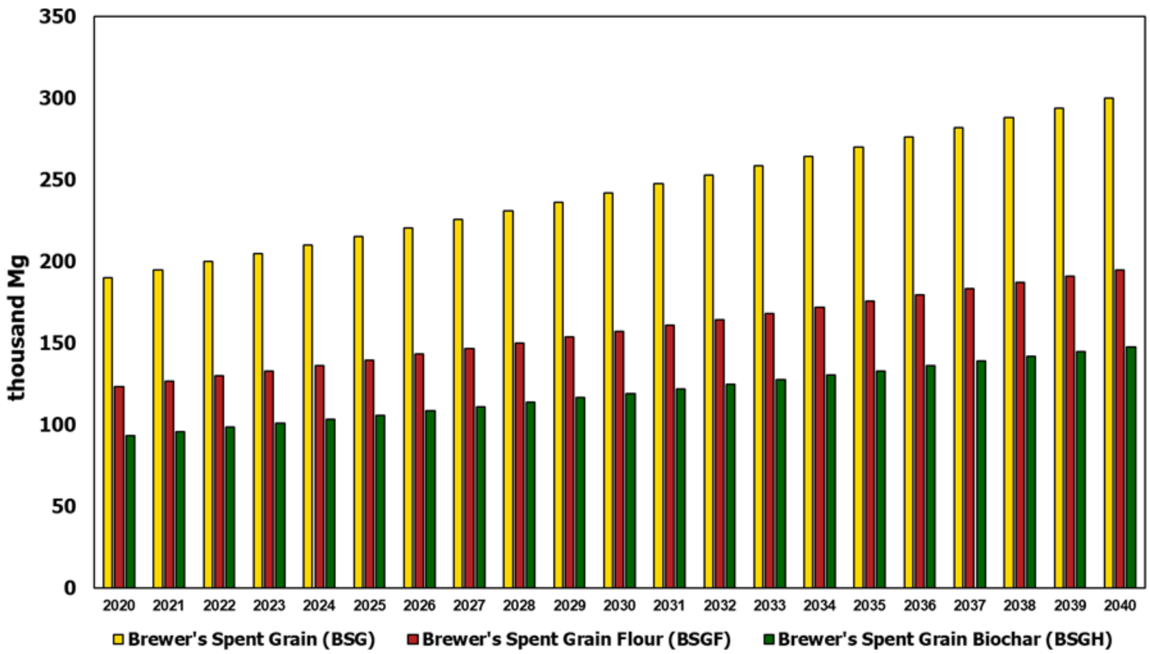


Fig. 6.6 South Africa's potential BSG, BSGF and BSGH production on a dry weight basis, 2020-2040

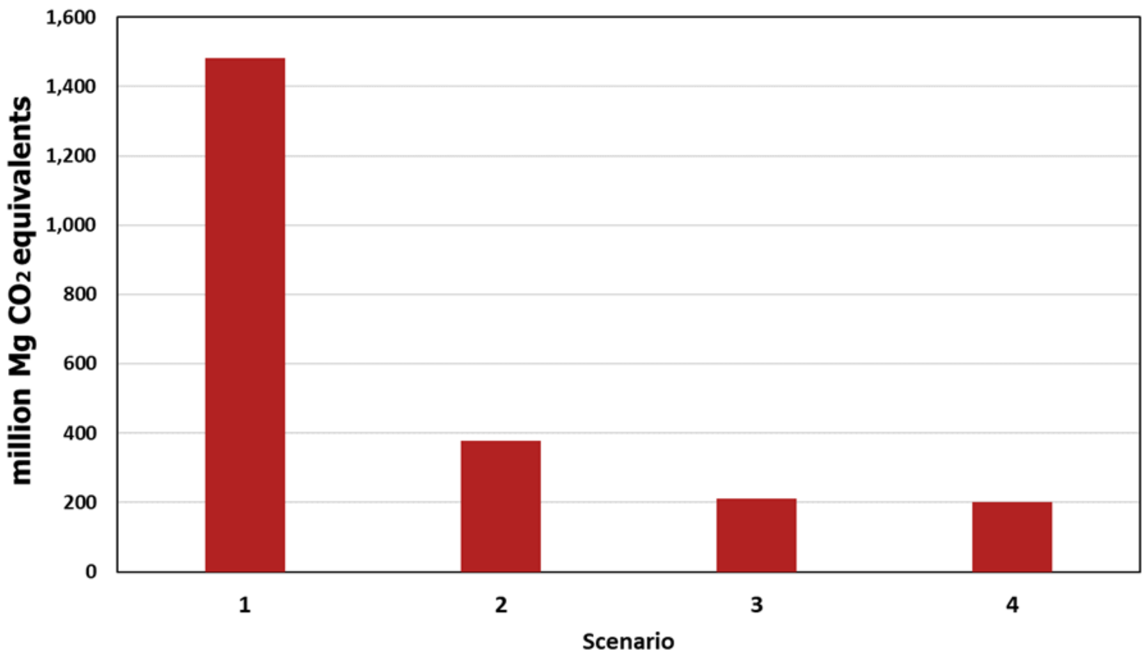


Fig. 6.7 Global warming potential under the 4 different scenarios for BSG usage from 2020 to 2040

Historically the beer market consumption volume increased with a CAGR of 2.7% between 2014 — 2018 according to [277]. The South African beer market (retail prices) is expected to increase at a CAGR of 5.48% per annum for the period 2019 to 2024. The average consumption per capita is set to increase at a CAGR of 5.61% per annum from 2014 to 2024 with a gradual dip to a CAGR of 4.35% per annum after peaking in 2024 [278]. In order to elucidate the environmental benefits of BSG valorization via biofuel or flour production, a comparison with landfilling and animal feeding was deemed necessary. Results shown in **Fig. 6.7** indicate that HTC route (Scenario 1) has almost 6.5 times as much global warming potential as either landfilling BSG or using it as animal feed. Flour production (scenario 2) would release almost twice the greenhouse emissions at a 20-year analytical time horizon. At over 1,400 million CO_{2eq} Scenario 1 is almost 3.9 times more harmful than Scenario 2. Landfilling or BSG usage as animal feed are clearly preferable from a purely environmental point of view. If the social benefit and nutrition welfare perspectives are added then flour production is a clear winner.

6.5 Conclusion

Africa is facing a myriad of challenges including food insecurity, environmental degradation, a lack of access to clean and modern energy. Hydrothermal carbonization (HTC) has gained worldwide research attention, but there are limited investigations on the potential of HTC derived biochar to address the challenges in Africa. Agro-industrial wastes such as brewers' spent grain (BSG) are underutilized and often their disposal is not environmentally friendly. The thermochemical conversion of BSG into biochar using HTC is a potential alternative for the valorization of this biomass. An equally viable route is to convert the BSG into a flour for the fortification of bread and pastry products. Bread formulations with up to 10% added brewer's spent grain flour are organoleptically acceptable and healthier.

This study is an attempt to evaluate BSG's potentiality as a food and renewable energy source. To determine which of the two routes has less impact on the environment thus enabling Africa to extract the most social benefit, the Global Warming Potential (GWP) of alternate routes were assessed. An assessment of the theoretical yields of biocoal and its potential energy from hydrothermally treated BSG from African countries has been provided. An easily implementable methodology for assessing present and future bioenergy potentials of BSG using official statistics has been given. The estimates given in this study suggest BSG alone cannot contribute a significant share to the energy demand in the African continent. All the BSG calculations up to the year 2040 show a considerable range in potential. BSG generation is estimated at about 699,000 Mg on a dry basis for 2020 at a continental level. At a 90% confidence level roughly 0.52 to 0.91 million Mg/yr can be anticipated. For the year 2040 BSG generation rate will be about 852,000 Mg/yr of BSG on average and 0.57 to 1.20 million Mg/yr at a 90% confidence level. Using South Africa as a case study, the GWP of BSG conversion to hydrochar at roughly 1,400 million CO_{2eq} from 2020 to 2040 is 390% higher than the alternative, BSG milling to flour. Flour production can be expected to have a lower carbon footprint.

Based on the estimations reported here, future studies are recommended to focus on developing novel solutions to the utilization of BSG in combination with other biomass materials that are relatively abundant if BSG energy recovery is to be substantial. These include solid waste, crop and animal residues. A supply chain structure and cost evaluations for such combinations should also be investigated. The financial feasibility of milling BSG for flour production should also be conducted for a more comprehensive assessment. As far as the large-scale utilization of BSG for bioenergy in Africa is concerned, it is unlikely that this material alone will be a viable feedstock for HTC due to its low availability.

Chapter 7: Conclusions and recommendations

The general and overall conclusions of this study together with recommendations for future studies are given in this chapter.

7.1 Overall Conclusions

Hydrothermal carbonization (HTC) is a wet thermochemical conversion process performed on any carbon or organic feedstock in the presence of subcritical water at an elevated temperature (180–300 °C) and pressure (above 1 MPa). HTC is versatile and can be applied to a range of feedstocks like the organic fraction of municipal solid waste, sewage sludge, animal waste and other high moisture content wastes such as brewer's spent grain. HTC is more advantageous for wet wastes as it makes the process of pre-drying unnecessary. Its suitability for developing nations cannot be overemphasized, it is a relatively cheaper waste-to-energy option to build and maintain. Zimbabwe is facing a several challenges including, poor MSW management, energy shortages, deforestation as well as other environmental problems linked to improper management of agro-industrial wastes. The diversion of some of this organic waste to thermochemical processes for bioenergy production can address Zimbabwe's woes. To date, several articles have focused on waste management options in Zimbabwe and estimations of biomass have been made. These studies have been limited in that they have not considered the financial viability and environmental impact of the proposed solutions. Furthermore, the biomass estimations have not considered the high variability in the estimation of biomass meaning a high level of uncertainty. There is thus a huge impetus to develop comprehensive and more reliable models that can predict the availability of feedstock for HTC. To this end, in this research work, a stochastic approach to address these concerns was adopted. The impact of HTC on greenhouse gas emissions, leachate generation and economic evaluation of the process were presented.

7.1.1 General conclusions

Chapter 2: The most readily available feedstocks for bioenergy production were estimated with their energy potential. It was concluded that previous estimates of available feedstocks were too optimistic and since the methods were deterministic, there is a lot of uncertainty in the quantities reported.

Chapter 3: Zimbabwe's MSW was characterized and coal-alternative fuel production via HTC modelled. The effect of coal-alternative fuel (made from the application of HTC on

MSW) co-combustion in coal-fired thermal power plants on air emissions was then investigated under some scenarios. Zimbabwe's MSW was found to contain a lot of organic portions and a high paper and plastics content. This plastic and paper content are beneficial for raising the calorific value of the final fuel product. Direct emissions (CO_2) from the nation-wide HTC-MSW management system will slightly reduce compared to the current situation. Huge reductions in direct methane emissions as waste will be diverted from landfills to HTC facilities are the most crucial advantages of introducing HTC.

Chapter 4: The avoided leachate from disposal sites was estimated. Owing to the diversion of MSW to coal-alternative fuel production, a significant reduction of leachate volume can be expected.

Chapter 5: BSG availability for HTC was estimated and the global warming potential of this system compared to current disposal methods. It was concluded that HTC would have a higher impact compared to alternative treatment methods such as using BSG for food (animals and humans) and landfilling.

Chapter 6: The viability of An HTC based waste management system was assessed. It was concluded that the private sector would not be likely succeed in this venture. A government-run system was more likely to succeed owing to the system being entitled to tax-exempt status. To boost the chances of success, a collaboration between the two sectors (highly skilled individuals from the private sector managing the process with tax breaks and other exemptions) would be necessary. Local governments can share the economic burden along with private investors thorough concessions or Build– operate–transfer (BOT) framework or running the enterprise as a strategic parastatal. Waste collection fees would have to be revised up and/or the use of pre-paid designated garbage bags introduced.

7.2 Recommendations for further studies

1. Zimbabweans' willingness to pay for an improved waste management system should be assessed.

2. Comprehensive assessments of other WTE technologies (incineration, pyrolysis and gasification) should be carried out to make a fair comparison with the proposed solution given in this research.
3. National policies should be assessed and recommendations for improvement made for the bioenergy sector.

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