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# Solid Waste Management and Waste-to-Energy Feasibility in Kigali

A Case Study of the Mpazi Rehousing  
Project

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Julia Ahlbin  
Ida Olofsson



Division of Water Resources Engineering  
Department of Building and Environmental Technology  
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By:

Julia Ahlbin

Ida Olofsson

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Division of Water Resources Engineering  
Department of Building & Environmental Technology  
Lund University  
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221 00 Lund, Sweden

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# Abstract

This master's thesis explores a Waste-to-Energy solution for Kigali, specifically focusing on the Mpazi Rehousing Project. Kigali faces challenges with Solid Waste Management (SWM) despite its reputation for cleanliness and efficient urban planning. It aims to transform biowaste into biogas, contributing to sustainable urban development and reducing waste at Nduba landfill. The research addresses three main questions: the current state of SWM in Kigali, the suitable operational parameters for a community-based biogas digester in Rwanda, and the biogas potential and investment costs for a village-scale fixed dome biogas digester in the Mpazi Rehousing Project. The study encompasses a comprehensive approach involving literature review, data analysis, field observations and stakeholder interviews. The results indicate significant potential for biogas production, estimating daily outputs of 42 m<sup>3</sup> for maximum resident capacity in Mpazi, titled *Scenario I*, and 36 m<sup>3</sup> at 85% capacity, titled *Scenario II*. The investment costs are projected to be approximately 10 100 USD for a 70 m<sup>3</sup> reactor and 8 600 USD for a 59 m<sup>3</sup> reactor. Implementing small-scale investments like the community-based biogas digester presented in this master's thesis, do not only present a more feasible and immediate solution for mitigating waste at Nduba Landfill, but also lays the groundwork for scaling up projects in the capital.

**Keywords:** Solid Waste Management; Nduba Landfill; Waste-to-energy; Biogas production; Fixed dome digester; Clean cooking; Rwanda Urban Development Program (RUDP); Mpazi Rehousing Project; Biogas investment calculation.

# Sammanfattning

Denna masteruppsats utforskar en "waste-to-energy"-lösning för Kigali, med särskilt fokus på Mpazi Rehousing Project. Kigali står inför utmaningar med avfallshantering trots sitt rykte för renlighet och effektiv stadsplanering. Målet är att omvandla bioavfall till biogas, vilket kan bidra till hållbar stadsutveckling och minska avfallet till Nduba deponin. Examensarbetet behandlar tre huvudsakliga frågor: den nuvarande situationen för avfallshantering, lämpliga driftsparametrar för en biogasanläggning i Rwanda och biogaspotentialen samt investeringskostnaderna för en fast kupolbiogasanläggning (fixed dome digester) i Mpazi Rehousing Project. Metodiken innefattar en litteraturundersökning, dataanalys, fältobservationer och intervjuer med aktörer. Resultaten visar på betydande potential för biogasproduktion, med uppskattade daglig produktion på 42 m<sup>3</sup> vid maximal kapacitet för invånare i Mpazi, benämnt *Scenario I*, och 36 m<sup>3</sup> vid 85% kapacitet, benämnt *Scenario II*. Investeringskostnaderna beräknas vara cirka 10 100 USD för en 70 m<sup>3</sup> reaktor och 8 600 USD för en 59 m<sup>3</sup> reaktor. Genom att implementera småskaliga investeringar såsom biogasanläggningen som beskrivs i denna masteruppsats, presenteras inte bara en mer genomförbar och omedelbar lösning för att minska avfallet vid huvudstadens deponi, utan läggs även grundarbetet för större projekt i Kigali.

## Incamake (Kinyarwanda)

Iyi nyandiko y'icyiciro cya kabiri cya kaminuza iriga ku gisubizo cyo guhindura imyanda mo ingufu mu mujyi wa Kigali, by'umwihariko igaruka ku mushinga wo gutuza abaturatione ba Mpazi. Kigali ihura n'ibibazo mu micungire y'imyanda nubwo izwiho isuku n'imitunganyirize y'imijyi neza. Intego ni uguhindura imyanda ibora mo gazi izwi nka biogaz, bigafasha mu iterambere rirambye ry'umujyi no kugabanya imyanda ku kimoteri cya Nduba. Ubushakashatsi bugamije gusubiza ibibazo bitatu by'ingenzi: uko ibijyanye n'imitungire y'imyanda bimeze muri Kigali muri iki gihe, ibipimo bikwiye byo gukoresha ikigega gikora biogaz ku rwego rw'umudugudu mu Rwanda, uburyo biogaz yakwakirwa n'ingano y'imari yashorwa mu bikoreho byo kuyikora kuburyo yahaza umudugudu wo mu mushinga wo gutuza abaturatione wa Mpazi. Ubu bushakashatsi bukoresha uburyo burambuye burimo isesengura ry'ibitabo, isesengura ry'ibipimo, gusura aho umushinga utekerezwa gushyirwa, ndetse no kuganira n'abafatite uruhare mu bijyanye n'ingingo z'ubu bushakashatsi. Ibisubizo byerekana ubushobozi bukomeye bwo kubyaza biogaz imyanda, bugaragaza umusaruro w'amametero kibe 42 m<sup>3</sup> ku munsu ku bushobozi bw'abaturatione ba Mpazi bungana n'abaturatione b'icyiciro cya mbere, byiswe *Scenario I* ndetse n'amametero kibe 36 ku bushobozi bwa 85%, byiswe *Scenario II*. Igiciro cy'ishoramari kibarirwa hafi ya 10,100 by'amadorari y'Amerika ku muyoboro wa 70 m<sup>3</sup> na 8,600 by'amadorari y'Amerika ku muyoboro wa 59 m<sup>3</sup>. Gushyira mu bikorwa uyumushinga w'ishoramari rito wo gushyira ingufu za biogaz nk'uko iyi nyandiko y'icyiciro cya kabiri cya kaminuza ibyerekana ntibizatanga gusa igisubizo cyihutirwa kandi kiboneka neza cyo kugabanya imyanda ku kimoteri cya Nduba, ahubwo bizanatanga umusingi wo kongera imishinga mu murwa mukuru.

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## Acronyms and abbreviations

AD	anaerobic digester
E-waste	electronic waste
GGGI	Global Green Growth Institute
GHG	greenhouse gases
HRT	hydraulic retention time
MINICT	Ministry of ICT and Innovation
MININFRA	Ministry of Infrastructure
MoE	Ministry of Environment
N	nitrogen
NDBP	National Domestic Biogas Program
P	phosphorous
REG	Rwanda Energy Group
REMA	Rwanda Environmental Management Authority
RUDP	Rwanda Urban Development Project
RURA	Rwanda Utilities Regulatory Authority
SIDA	Swedish International Development Cooperation Agency
SWM	solid waste management
TS	total solids
VS	volatile solids
WASAC	Water & Sanitation Cooperation
WASH	water, sanitation and hygiene

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# 1 Introduction

Solid waste generation poses a significant global challenge today, affecting local environments, ecosystems, public health and socioeconomic well-being on a worldwide scale. According to the World Bank, approximately 2.01 billion tons of waste were generated in 2018, and is expected to rise to 3.40 billion tons by 2050 (Kaza et al. 2018). Addressing this issue with sustainable solutions is a top priority globally. A country with successes in collection of solid waste is Rwanda, with its capital Kigali recognized as the cleanest city of Africa.

Despite being one of the continent's smallest countries in terms of area, its population of roughly 13 million makes Rwanda the most densely populated country on the continent. Often referred to as the *Singapore of Africa*, Rwanda is praised for its efficient governance, rapid economic growth and successfully urban planning. Specifically, its cleanliness stands out as the most prominent reason for this comparison. Initiatives such as plastic bag ban, the national cleaning day called *Umuganda*, strict regulations, awareness campaigns and green investments have earned Kigali the reputation of being the cleanest city in Africa. With the formulation of national strategies, policies and masterplans, the Government of Rwanda places greatly emphasis on developing Solid Waste Management (SWM). Despite Kigali outperforming its neighboring capitals over the last decade with significant progress in waste collection coverage, SWM remains a key focus area for improvement.

The municipality City of Kigali commissioned a feasibility study for the development of SWM in Kigali, which was sponsored by Swedfund and conducted by the consulting company COWI in 2019. The study investigates the possibilities of upgrading the currently semi-controlled SWM system, Nduba landfill, into a sanitary landfill. Currently, City of Kigali is still searching for funding to launch the project. As a result of these findings, our study is not intended to develop the collection, transport or management of the SWM in Kigali. Instead, it aims to focus on mitigating the waste transported to the landfill.

As urbanization in Kigali continues to increase, issues regarding inadequate infrastructure and informal settlements arise. In alignment with the Rwanda Urban Development Project II (RUDPII) launched by the Government of Rwanda, Skat Consulting Rwanda is conducting a pilot project called *Mpazi Rehousing Project*. This project is an unplanned settlement upgrade, and it extends beyond a rehousing project; investments are also targeting critical areas such as stormwater management and environmental resilience. Upon being introduced to this sustainable and modern approach to urban development, the Mpazi Rehousing Project serves as an ideal case study for investigating potential waste-to-energy solutions.

## 1.1 Aim and Research Questions

The specific intent of this master's thesis is to formulate a feasible waste-to-energy solution for Kigali, with the purpose of conducting an in-depth examination of the achievements and challenges of the capital's Solid Waste Management (SWM) practices. This solution will align with City of Kigali's aspiration of sustainable urban development along with mitigating the volume of solid waste currently deposited at the Nduba landfill. This is achieved through a collaboration with the company Skat Consulting Rwanda and their ongoing urban pilot project in Kigali, *Mpazi Rehousing Project*, serving as a case study. The waste-to-energy solution assessed is the possibility of transforming biowaste to biogas through the implementation of a village-scale biogas digester. In order to accomplish the aim, the following research questions will be answered:

1. How is the solid waste from households collected and transported in Kigali, and how is the waste currently managed at Nduba landfill?
2. a) What operational parameters and design are suitable for an urban community-based biogas digester in Rwanda?  
b) How have national initiatives contributed to the biogas development?
3. Considering the ongoing urban upgrade project in Mpazi, what are the estimated biogas potential and its investment costs?

## 1.2 Scope and Delimitations

This report, a master's thesis completed over the course of one semester, is founded on a literature review supplemented by interviews and field observations conducted during a ten-week field visit in Rwanda. Geographically, the scope is confined to the examination of SWM practices within the city of Kigali. Regarding biogas potential, it is essential to highlight that the study does not explore the microbial reactions involved in biogas production or offer detailed technical descriptions. Furthermore, while the study proposes a design for a fixed dome digester, it does not provide precise measurements; instead, it presents approximate energy production and cost estimates. Finally, it is important to acknowledge that numerous estimations were necessary in this study due to absence of valid data. These limitations are acknowledged and considered within the framework of this research.

## 1.3 Disposition

The **Methodology** section outlines the research methods used, including the calculations and data collection such as literature and field work. The findings are presented in three chapters, each addressing a specific research question. **Chapter 3** is a descriptive chapter that summarizes the SWM practices in Kigali. **Chapter 4** explains the basics of community-based biogas production together with the biogas development initiatives in Rwanda. **Chapter 5** presents the Mpazi Rehousing Project developed by Skat, including the results from the calculations of biogas potential and investment cost. The **Discussion** is found in Chapter 6, followed by the **Conclusion** in the last chapter. Lastly, the Appendix is included at the end of this master's thesis.

## 2 Methodology

This master's thesis was developed using a mix-method approach, consisting of both qualitative and quantitative research to gather and analyze data.

*Research question 1* regarding SWM in Kigali is a descriptive question. To answer it, interviews with stakeholders were conducted, site observations were performed and relevant literature was reviewed to gain an understanding of the current practices, technologies and challenges in solid waste collection, transportation and management. A site visit to Nduba landfill, guided by WASAC, served as the primary data collection method for SWM in Kigali.

*Research question 2* regarding biogas in Rwanda is divided into two parts: an explanatory question (2a) and a descriptive question (2b). For 2a, biogas production theory is explained and a feasible design for a community-based biogas digester suited for the urban setting in Kigali is chosen. This was conducted through a literature review and studying case studies, examining successful small-scale biogas projects in similar conditions to identify best practices and key success factors. To answer 2b, a literature review of biogas development initiatives in Rwanda was conducted, complemented by an interview with experts at Rwanda Energy Group (REG).

*Research question 3* regarding the urban upgrade project in Mpazi is an explanatory question. Through a site visit to Mpazi neighborhood, interviews with Skat and residents in Mpazi along with a literature review, the production and investment cost for a biogas digester could be estimated.

### **Description of Case Study - Mpazi Rehousing Project**

The Mpazi neighborhood in Kigali, spanning 4 hectares, previously housed approximately 2 000 residents in informal settlements. The Mpazi Rehousing Project aims to redevelop this area through two phases: Phase I (Model House and Blocks A-D) and Phase II (Blocks E-W).

Phase I involved clearing part of the informal settlements and building the first five structures including a "Model House" that served as a pilot for evaluating materials and living conditions. Phase II will clear additional settlements and prepare for the construction of the remaining 19 blocks. The project also includes plans for a market, recreational area, and road development.

### **2.1 Data Collection**

This report is based on both primary and secondary data. Collection methods conducted are a literature review, interviews and site observations. The field work to Rwanda was possible through the partnership between Lund University and University of Rwanda. It was mainly through the support of professors and PhD students at University of Rwanda that connections with stakeholders interviews and site observations could be conducted. Additionally, the collaboration with Skat Consulting Rwanda resulted in the case study of Mpazi Rehousing Project.

### 2.1.1 Literature Review

This master’s thesis began with a comprehensive literature review that incorporated both conceptual and empirical studies. Conceptual literature, including theories, technologies and key concepts, was used in order to deepen understanding for the calculations and analyses required for data interpretation. These were based on sources from scientific papers or technical journals, academical lectures, publications from governments, ministries or municipalities, interest organizations or companies and public statistics. Additionally, empirical studies were examined to track the development of the local context and conditions. For this, previous research within the same geographical region or topic area was studied. To ensure the relevance of all literature cited, none of the sources utilized were older than 20 years, with the earliest dating back to 2005. The primary search engines employed for the literature review have been LUB-search and Google. Key words frequently used were: solid waste management in Rwanda, City of Kigali, MININFRA, WASAC, biogas potential calculation, fixed dome biogas digester, investment calculation for small-scale biogas, biogas in Rwanda.

### 2.1.2 Interviews

During the ten-week field work in Kigali, several different stakeholders were contacted, primarily with assistance from the University of Rwanda. Table 1 lists the stakeholders involved, either in person or online, along with the main topic discussed. All interviews were conducted in English or Swedish, except for the interviews with the two residents in Mpazi. For these two, a interpreter from Skat translated throughout the interview.

Table 1: List of involved stakeholder in Kigali and contribution to study.

<b>Interviewee</b>	<b>Contribution to study</b>
Anirudh Rajashekar, author of SWM report	SWM in Kigali
Clement Musabe, REG	Biogas in Rwanda
Gatete Pascal, Depot Kalisimbi	SWM at Nduba landfill
Jean Bosco, City of Kigali	Environmental inspection
Jean Marcel Uwaremwe, Skat	Mpazi rehousing project
John Mugabo, City of Kigali	SWM
Juvenal Mukurarinda, GGGI	SWM
Karin Eberle, former advisor for Swedfund	SWM, foreign aid projects
Marie Josee Nyiraburanga, WASAC	SWM
Pacifique Hagumimana, Skat	Mpazi Rehousing Project
Teresi Mukabideri, resident in Mpazi	SWM and cooking practices
Vestine Umutesi, resident in Mpazi	SWM and cooking practices

### 2.1.3 Field Observations

The field work in Kigali can be framed as a ten-week long observation period, consisting of both structured and unstructured observations. Throughout the field work, notes and pictures were taken, accumulating information about the SWM in Kigali and Mpazi Rehousing Project. With the help from stakeholders active in Kigali, all found through University of Rwanda, three site visits were conducted, see Table 2.

Table 2: Site visits in Kigali.

Date	Site visits
2024-03-06	Mpazi Rehousing Project, guided by Water Resource Board
2024-03-21	Nduba landfill, guided by WASAC
2024-03-26	Mpazi Rehousing Project, guided by Skat

## 2.2 Calculations and Data Processing

This section outlines the different approaches used for processing data, including the conversion of literature findings, interview responses and observations into qualitative and quantitative results.

### 2.2.1 Calculations of Residents in Mpazi

The estimation of the resident population was based on data provided by Skat, including number of available units together with the size and type of unit. Skat assumed that each resident requires approximately 9 m<sup>2</sup> of space (Uwaremwe 2024). Different types of data was provided for each phase. For Phase I, the total household area of the blocks is given in m<sup>2</sup>. For Phase II, the total number of units was multiplied by the maximum number of residents for each unit to predict the total resident count. In agreement with Skat, the total resident count was performed for both maximum capacity of the units, titled *Scenario I* and at 85% capacity, titled *Scenario II*. This was motivated by considering potential variations in occupancy rates.

### 2.2.2 Calculations of Biogas Potential

The methodology is presented for calculations regarding generated biowaste, quantity and quality of feedstock together with determination of biogas digester volume and the daily biogas production. In order to apply this for the local conditions of Mpazi Rehousing Project, certain characteristics of the biowaste was needed. This was accomplished through a literature study, with some complements from interviews.

#### A. Biowaste Generated in Mpazi

The waste generation, collection coverage and fraction of biowaste was found through the literature study and also discussed with stakeholders for confirmation. The main source of data for these values was an article on the performance of SWM in East Africa, with Kigali

serving as a case study (Kabera, Wilson, et al. 2019).

The biowaste per capita in Kigali was calculated using Equation 1. To determine the total generated biowaste in Mpazi Rehousing Project, the generated biowaste per capita and estimated number of residents were needed, see Equation 2. The quantity of waste per day is expressed in wet weight  $ww$ . The generated waste per capita is 0.57 kg/day and the fraction of biowaste 0.7 (ibid.).

$$M_b = M_w \times f \quad (1)$$

$$M_{b,tot} = M_b \times n \quad (2)$$

Where:

$M_b$  = biowaste per capita [kg/day ww]

$M_c$  = waste per capita [kg/day ww]

$f$  = fraction of biowaste

$M_{b,tot}$  = total generated biowaste [kg/day ww]

$n$  = number of residents in Mpazi

## B. Quantity of Feedstock

To calculate the volume of the biogas digester, the quantity of substrate, or *feedstock*, first needed to be estimated. The method is based on the calculations given in Mukumba et al. (2013), see Equation 3. The substrate-to-water ratio needed was assumed to be 1:1 when using food waste as feedstock (Somashekar et al. 2014).

$$Q_w = M_{tot} \times (x + y) \quad (3)$$

Where:

$Q_w$  = substrate flow rate [kg/day ww]

$M_{tot}$  = total generated biowaste [kg/day ww]

$x, y$  = ratio x:y of water to substrate

## C. Sizing the Biogas Digester

In an extensive report made by Mucyo (2013), biogas technology for SWM is examined, with Kigali as a case study. This report presents findings from food waste collected from households, which were studied and later analyzed in a laboratory biogas digester. The aim

was to understand the composition of typical domestic food waste mix in Kigali together with its availability, suitability and utilization for biogas production. In the Mpazi Rehousing Project, the feedstock of the AD was based on food waste collected in this neighborhood which is situated in central Kigali.

The total volume of feedstock input was determined using Equation 4, under the assumption that one kilogram of substrate is equivalent to one liter (1 kg = 1 L) (Somashekar et al. 2014). The Hydraulic Retention Time  $HRT$  quantifies the duration that the feedstock resides within the reactor dome. Subsequently, the digester's capacity equals the total volume of feedstock input, as illustrated in Equation 5 (Mukumba et al. 2013). The optimum biochemical methane potential is reached between day 23 to 30, resulting in the conclusion that the suitable  $HRT$  is estimated to 30 days (Mucyo 2013).

$$V_{input} = \frac{Q_v}{1000} \times HRT \quad (4)$$

$$V_{digester} = V_{input} \quad (5)$$

Where:

$$V_{input} = \text{total volume of input [m}^3\text{]}$$

$$Q_v = \text{substrate flow rate [L/day]}$$

$$HRT = \text{hydraulic retention time [days]}$$

$$V_{digester} = \text{total volume of digester [m}^3\text{]}$$

#### D. Feedstock Characteristics

Before determining the daily biogas production, the generated biowaste needed to be converted into Volatile Solids  $M_{VS}$ , expressed in  $kg\ VS/day$ , representing the total amount of organic matter. This was performed by first calculating the Total Solids  $M_{TS}$  of the feedstock by multiplying the generated biowaste by the fraction of Total Solids  $TS$ , see Equation 6. Subsequently, in Equation 7, the Volatile Solids  $M_{VS}$  are determined by multiplying the Total Solids  $TS$  by the fraction of Volatile Solids  $VS$ . For typical household food waste in Kigali, the Total Solids is 19% and the Volatile Solids is 90.12% (ibid.).

$$M_{TS} = M_{tot} \times TS \quad (6)$$

$$M_{VS} = M_{TS} \times VS \quad (7)$$

Where:

$$M_{TS} = \text{Total Solids [kg TS/day]}$$

TS = fraction of Total Solids (%)

$M_{VS}$  = Volatile Solids [kg VS/day]

VS = fraction of Volatile Solids (%)

### E. Daily Biogas Production

At last, when the feedstock characteristics were known, the daily generation of biogas  $G$  from the digester was estimated, see Equation 8 (Vögeli et al. 2014). The biogas yield  $Y$  of the feedstock had to be determined based on the type of substrate used, here expressed in  $m^3/kg$  VS. The energy content  $E$  of the daily biogas production was also approximated, see Equation 9. The biogas yield  $Y$  for AD of food waste from households in Kigali, the maximum methane yield is  $0.209 m^3/kg$  VS at  $25^\circ C$  (Mucyo 2013). The Calorific Value of biogas is  $6 kWh/m^3$  (Vögeli et al. 2014).

$$G = M_{VS} \times Y \quad (8)$$

$$E = G \times CV \quad (9)$$

Where:

$G$  = biogas generated each day [ $m^3/day$ ]

$M_{VS}$  = Volatile Solids [kg VS/day]

$Y$  = biogas yield [ $m^3/kg$  VS]

$E$  = Energy content of biogas [kWh/day]

$CV$  = Calorific Value [kWh/ $m^3$ ]

### 2.2.3 Investment Calculation

A literature study to create an investment calculation for the potential fixed dome biogas digester was made. It was assumed that biogas digesters with the same design in other Sub-Saharan countries could be compared. This assumption was based on the comparable cost of materials across these countries and the difficulty in finding sufficient examples exclusively within Rwanda. The comparison was done between four sources: the first being the National Domestic Biogas Plan (NDBP) in Rwanda made by MININFRA together with SNV (Gaddefa et al. 2006), the second a feasibility study for NDBP in Burkina Faso (GTZ 2007), the third a new biogas investment project in South Ethiopia (Dekelver et al. 2023) and the last one from a biogas program in Sub-Saharan Africa with Uganda as a case study (Renwick et al. 2007). The components in the different investments calculations were compared and their relevance evaluated, which resulted in an economic estimate for the Mpazi Rehousing Project. The two scenarios of the predicted number of residents in the Mpazi Rehousing Project determined the required reactor volume for the digester.

A limitation of the investment calculation was the reliance on data sources that are over 15 years old for three out of the four references cited in the literature study. The sources are all based on Sub-Saharan countries, but national differences have not been considered when comparing material and financial situation. Due to lack of data and difficulties for proper estimations, the transport cost was excluded. It should be noted however, that freight services and unpredictability in transport time have more pronounced impact on landlocked economies (Amigun et al. 2010). The cost for the construction of the biogas digester was based on the investment calculation from the project in Rwanda (Gaddefa et al. 2006), including inflation change from 2007 to 2024.

Several assumptions were made when calculating the investment cost. Firstly, due to variations in reactor volume among the compared digesters, an estimate was made of the quantity per cubic meter. This was subsequently multiplied by the calculated reactor volume from the two scenarios predicted for the Mpazi Rehousing Project. Secondly, differences in the units of construction materials and components between the compared digesters required conversions to determine an average from the literature values; for example average sizes of a brick and a barrow filled with sand were assumed. Also, when constructing a low-tech biogas digester, the relative investment cost decreases exponentially with an increase in digester size (Amigun et al. 2010). This factor was overlooked when the calculations for the investment cost were developed.

In order to validate the estimated investment calculation, a comparison with literature values presented in Kabera, Nishimwe, et al. (2016) was made. Investment costs found from the report were based on reactor volumes of 4 and 6 m<sup>3</sup>. Therefore, a cost per cubic meter was calculated and then multiplied with the reactor volumes estimated for Scenario I and II. Since the prices from Kabera, Nishimwe, et al. (ibid.) are from 8 years ago, adjustments have been made to account for inflation changes.

#### **2.2.4 Cost of Energy**

By using the investment cost and a 20-year lifespan of the digester based on Vögeli et al. (2014), the daily cost was estimated. It is essential to mention that operational and maintenance expenses are excluded in the daily cost estimation. The exclusion is motivated by uncertainties surrounding the future operation and utilization of the digester, as well as by a lack of data. By dividing the daily cost with the estimated biogas production, an estimate of the energy cost for the biogas produced in Mpazi Rehousing Project was obtained.

The estimated energy cost of biogas was compared with Liquefied Petroleum Gas (LPG), as LPG is the most commonly used cooking gas in Kigali (ibid.). To determine the energy cost of LPG, the latest price reported by RURA (2021) was divided by the calorific value sourced from ELGAS (2024).

## 3 Results

The results are presented in the next three sections. The first regarding SWM practices in Kigali, the second about a community-based biogas digester system and lastly, presenting the prospects for biogas in Mpazi Rehousing Project.

### 3.1 Solid Waste Management in Kigali

For an in-depth examination of current SWM practices in Kigali, it is important to state that only solid waste collected from households will be considered in this master's thesis.

#### 3.1.1 Stakeholders

To comprehend the SWM practices, it is first essential to clarify the stakeholders involved. The existing institutional arrangement encompasses several stakeholders, from national to local government institutions, inter-governmental organizations and private sector with support from international development agencies. This section will introduce the key stakeholders. The majority of this information was gathered through interviews with the stakeholders listed in Table 1.

The Government of Rwanda bears the primary responsibility for the development of the SWM. To organize this fundamental service effectively, the responsibility is delegated to various governmental bodies. The ministries involved in the SWM are the Ministry of Infrastructure (MININFRA), the Ministry of Environment (MoE) and the Ministry of ICT and Innovation (MINICT). MININFRA oversees the coordination, monitoring and evaluation of SWM, as well as the formulation of relevant policies. Support for this institution is credited to the government-owned companies Water and Sanitation Corporation (WASAC) and Rwanda Energy Group (REG). The MoE supports MININFRA with guidelines and policies together with raising awareness at district level. Rwanda Environmental Management Authority (REMA), an affiliated agency of MoE, assists MoE at district level and perform sanitary inspections of hazardous waste. The third ministry in question, MINICT, shares similar responsibilities with MoE but focuses primarily on e-waste management. Under this ministry, Rwanda Utilities Regulatory Authority (RURA) aids MININFRA in developing standards for SWM.

At the district level, the municipality City of Kigali has the primary responsibility for the capital's SWM and implementing national laws and policies. Their main focus is the collection and transportation of waste throughout Kigali. To achieve this, the municipality has contracted the service of 13 waste collection companies, each assigned to cover different sectors of the city, and tasked RURA to regulate the collection. Waste management and disposal duties have been delegated by the City of Kigali to WASAC. All domestic and commercial solid waste generated in Kigali is transported to Nduba landfill, a facility jointly owned by the City of Kigali and WASAC. On behalf of WASAC, the private company Depot Kalisimbi currently receives and manages waste at Nduba landfill. Additionally, REMA regulates the environmental inspection of Kigali and Nduba landfill.

International stakeholders also play a vital role for this field. Primary support is provided by international foreign aid and development agencies such as the GIZ (Deutsche Gesellschaft

für Internationale Zusammenarbeit), USAID (United States Agency for International Development) and SIDA (Swedish International Development Cooperation Agency) as well as the European Union. Additionally, in recent years, an influential finance institution for SWM in Kigali in recent years has been Swedish state-owned Swedfund, contributing to international development by investing in sustainable businesses. The feasibility study of Nduba landfill mentioned previously, was funded by Swedfund and conducted by COWI. Another involved entity is the Global Green Growth Institute (GGGI), operating as a treaty-based inter-governmental organization committed to fostering sustainable and robust economic development in emerging economies. A summary of the main stakeholders and their relationships are presented in Figure 1.

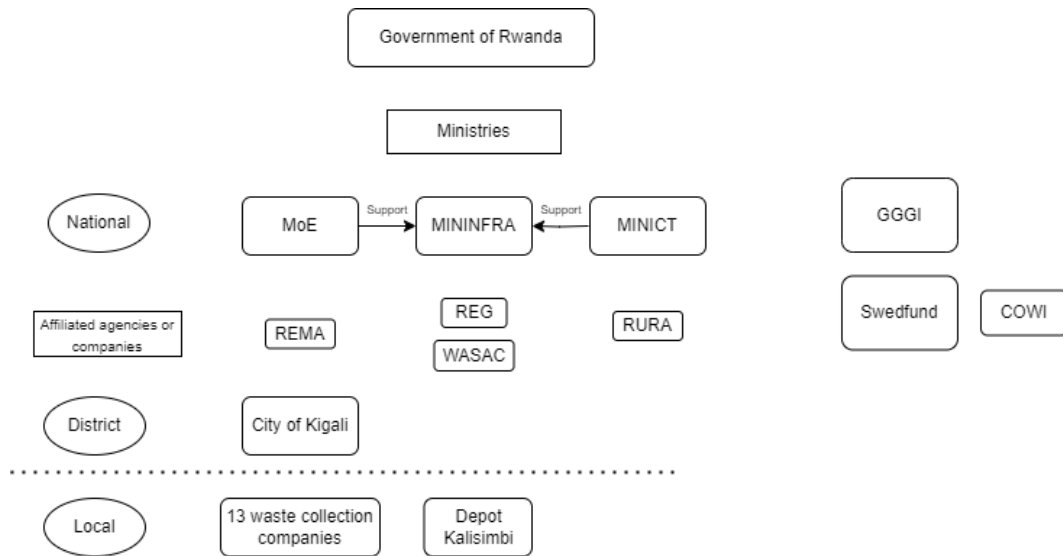


Figure 1: Mapping of stakeholders.

### 3.1.2 From Household Waste to Deposition

There is an initiative in Rwanda called "The public cleaning day", which refers to a designated day Rwandans come together to clean their public spaces. In Rwanda, it's known as *Umuganda*, which is a Kinyarwanda term meaning "coming together in common purpose to achieve a goal". Umuganda takes place on the last Saturday of every month and is a national day of community service where citizens participate in activities such as cleaning streets, planting trees and repairing infrastructure. It's a significant part of Rwandan culture and plays a crucial role in promoting community unity and social cohesion as well as preventing littering in urban and natural areas.

As stated by Mugabo (2024), even if there is a public awareness of minimizing littering, waste generation has not decreased. The average waste generated per capita in Kigali is approximately 0.6 kg/day, resulting in a total of almost 640 tonnes/day in the city. Within this waste stream, approximately 70-80% consists of biowaste, emphasizing its significance for SWM. Over the past few years, most of the municipal efforts has concentrated on expanding waste collection coverage in the capital. Collection coverage reached 88% 2019. if comparing Rwanda with its neighboring countries, Kabera, Wilson, et al. (2019) shows

that collection coverage is 40% in Dar es Salaam, Tanzania; 50% in Kampala, Uganda and 52% in Nairobi, Kenya. The development of solid waste components in Kigali are presented in Table 3.

Table 3: Solid waste component estimates for households in Kigali from previous studies.

<b>Waste component</b>	<b>Mucyo (2013)</b>	<b>Kabera (2019)</b>	<b>Pascal (2024)</b>	<b>Mukurarinda (2024)</b>
Generation per capita (kg/day)	0.61	0.57		
Generation (t/day)	450	638		
Fraction biowaste	0.70	0.70	0.78-0.80	
Biowaste per capita (kg/day)	0.43	0.40		
Collected (t/day)	198	561	600	550-650
Collection coverage	0.44	0.88		

Today, the greatest challenge for SWM in the city is to develop an effective solution for separation-at-source, as all domestic and commercial waste is currently mixed, according to Bosco (2024). During the last years, the City of Kigali has started to upgrade the capital’s public waste bins. They now have to consist of two bins, one for biowaste and one for non-biowaste, see Figure 2. The households should separate their food waste from the residual waste, but it is not being followed due to insufficient regulations, lack of awareness and that collection companies operate in trucks with only single-compartments. Initiatives to upgrade the sorting system at household level are under development and seek funding by the government. For example, newly developed districts are required to install a two-bin system.

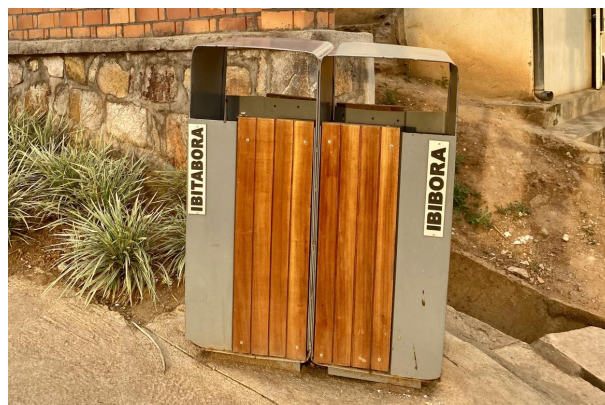


Figure 2: New public waste bins separating biowaste (left) and non-biowaste (right).

The waste collection companies in the city collect the mixed waste into a single-compartment

truck, see Figure 3. In Kigali, 13 waste collection companies operate, designated to specific areas for collection once a week (Rajashekar et al. 2019). As stated earlier, the collection rate has increased over the past 10 years, now covering up to 88%. Today, approximately 600 tonnes/day are collected and transported to Nduba landfill.



Figure 3: Weekly waste collection in Kacyiru, Kigali.

### 3.1.3 Management and Development of Nduba Landfill

Until 2012, all the waste collected in Kigali was transported to Nyanza landfill located in the Kagarama sector of Kicukiro district (Bosco 2024). It served as an open dumpsite with almost no maintenance, causing significant harm to the surrounding environment and human health. Consequently, the landfill was closed in 2012 to rehabilitate the area and to relocate it farther from the city. As a result, the City of Kigali opened Nduba Landfill in 2012, situated in the Nduba sector of Gasabo district. From 2012 to 2020, Nduba landfill was under the operation of City of Kigali with minimal maintenance, functioning as a dumpsite, see Figure 4. There was a lack of management of leachate water, landfill gas and soil layers, again resulting in harmful effects on the surrounding community and environment.



Figure 4: Collage of photographs of Nduba landfill between 2012-2020, in the Nduba landfill office.

In 2020, operation of the landfill was transferred to WASAC, with the company Depot Kalisimbi appointed as managing contractor. Depot Kalisimbi has more than a hundred employees onsite and has implemented various remediation measures to enhance landfill management, including mapping out the area with topography and roads, see Figure 5 (Pascal 2024). WASAC has also ensured the construction of access roads, established channels and ponds for leachate water, implemented soil covering to mitigate odors and control flies along with creating gardens of trees and fruits (Nyraburanga 2024). The change in landfill management has improved conditions at the site, transforming it from an open dumpsite to a semi-controlled landfill. However, Nduba landfill is not a sanitary landfill since environmental impact is not minimized (Rajashekar 2024).



Figure 5: Topographic map of Nduba landfill site (left) together with its legend (right) made by Depot Kalisimbi, in the Nduba landfill office.

The Nduba landfill is located atop a hill, approximately 15 km from the city center, with the final 4 km of the transportation route being unpaved. This last segment is a heavily trafficked hilly road that significantly impacts the surrounding community, exposing them to polluted air containing exhaust gases and dust from the road, as depicted in Figure 6.



Figure 6: Unpaved road leading up to Nduba landfill.

Depot Kalisimbi implements regulations and ensures that only the collection companies transporting domestic or commercial waste are permitted entry for waste disposal. If a truck were to carry hazardous waste, such as e-waste or medical waste, the associated collection company would be forced to pay a fee and be reported to City of Kigali. Upon entry, the solid waste is emptied from the compartments in a designated area onsite.

### Recycling Initiatives and Limitations of Waste Treatment

To date, no substantial sorting of recyclables or biowaste occurs at Nduba landfill (Pascal 2024). Consequently, Nduba landfill is currently not prepared to receive separated waste. However, Depot Kalisimbi has initiated a pilot project aiming at assessing the value of recyclables in Kigali. Employees sort a portion of the waste by identifying recyclable materials such as plastics, metals, and cartons, and organizing them into large bags, as shown in Figure 7. These recyclables are later transported to a small-scale recycling facility in the city.



Figure 7: A fraction of the recyclables being sorted in large bags.

After the small-scale sorting by hand, employees at Depot Kalisimbi manually perform a chemical treatment by spraying insecticide on the received waste (Nyiraburanga 2024). This helps prevent odor, flies, and other insects, as shown in Figure 8. Apart from the use of insecticide, no other treatment method is applied to the waste.



Figure 8: Manual chemical treatment on the received waste to prevent flies.

### **Waste Deposition**

The final step of handling solid waste at Nduba landfill is deposition. Initially, the waste is deposited in a designated area over a two-day period. Subsequently, over the next two days the waste is spread out and compacted, as can be seen in Figure 9. Each layer of waste, typically about 20 cm thick, is covered with soil transported from a site located five minutes away from the landfill. The schedule for these activities is determined based on weather conditions, with each layer taking approximately two weeks to complete (Nyiraburanga 2024). In Figure 10, the layers of waste and soil have accumulated to a height of six meters.



Figure 9: Machines spreading and compacting waste onsite. Marabou storks are common.



Figure 10: Deposition layers forming hills.

### **Leachate Water**

The water that filters through the waste at Nduba landfill becomes contaminated with dissolved and suspended substances, resulting in what is known as leachate water. It has a complex composition of a variety of pollutants, including organic and inorganic compounds, heavy metals, pathogens and toxins. The movement of leachate water within the landfill

is influenced by factors such as precipitation, waste composition and landfill design. It is of great importance that the leachate water is being captured due to its high risk of groundwater and soil contamination which can pose significant health risks to surrounding communities and ecosystems.

The landfill is strategically located on a hill to minimize the risk of contaminating the groundwater (Bosco 2024). Open channels have been implemented that directs the leachate water to constructed large scale ponds, see Figure 11 (Nyiraburanga 2024). No treatment method is applied to the contaminated water, instead the ponds serve as a permanent reservoir. A pond is built onsite and used until it is considered full. Currently, three have been excavated and if needed, more can be dredged. Samples are regularly collected from nearby streams to monitor potential groundwater contamination. Based on observations during the site visit, the ponds appeared well-maintained, with minimal odor and no visible flies (ibid.).



Figure 11: One of the three ponds designated for the storage of leachate water.

### **GGGI's Project: Waste to Resources**

In 2021, the "Waste to Resources" initiative was launched by the organization GGGI in collaboration with City of Kigali to improve municipal solid and hazardous waste (Mukurarinda 2024). The Government of the grand Duchy of Luxembourg supports this projects with a budget of four million euros. The three-year project finishing this year centers around three main stations adjacent to the Nduba landfill: a weighing bridge, a sorting machine and a composting site, presented in Figure 12. When the implementation is completed, the management of the project will be handed over to City of Kigali.



Figure 12: Plans of *Nduba sorting facility* included in the project "Waste to Resources" implemented by GGGI.

The weighing bridge, operational since December 2023, tracks the volume of waste entering and leaving the landfill in order to measure the amount of waste that Nduba landfill receives, see Figure 13. By steadily compiling a database of solid waste from the capital, it has significantly enhanced data collection efforts of SWM (Mukurarinda 2024).



Figure 13: The recently installed weighing bridge.

Meanwhile, the sorting machine seen in Figure 14, nearing completion, will through its sorting drum automate the separation process, distinguishing metals, e-waste, recyclables and biowaste. Presently, this task relies on manual labor, neglecting biowaste. With the sorting machine's deployment, a notable reduction in waste deposited at Nduba is anticipated. Biowaste will undergo a transformation at the third station, a designated composting site.

There, a vast land space is prepared to convert biowaste into biofertilizer, embodying the project's commitment to turn waste into resource (Mukurarinda 2024).



Figure 14: Construction in progress of the new sorting machine.

## 3.2 A community-based biogas digester system

The energy mix in Rwanda is highly dependent on biomass from forestry due to the traditional way of cooking using firewood or charcoal. Therefore, the Government of Rwanda plans to reduce the dependency on traditional cooking technologies, using biomass from natural forest, from 79% to 42% by 2024 (REG 2023). The aim is to replace the firewood and charcoal with clean cooking fuel, thereby enhancing public health together with protecting natural resources and the environment. Given the high cost of electricity relative to people's incomes, cooking gas has emerged as a viable solution (Musabe 2024). Biogas, as a renewable energy source, offers an alternative fuel option and holds promise for meeting sustainable energy demands.

### 3.2.1 An Introduction to Biogas Production

There exist endless of methods to transform waste into resource: recycling or upcycling, reparation, industrial symbiosis, incineration, composting and anaerobic digestion to mention some. This chapter will focus specifically on anaerobic digestion (AD). Using an engineered strategy and regulated facilities, AD is processing biodegradable materials in reactor domes free of oxygen, referred to as digesters, to generate biogas. Understanding AD starts with comparing it to another microbiological waste management solution - composting. The key distinction between these two methods is the presence of oxygen. While both composting and AD yield nutrient-rich biofertilizer, AD also generates renewable energy in the form of biogas.

#### Chemical Dynamics

When microorganisms decompose in an aerobic environment, carbon dioxide and water will be produced. However, if oxygen exposure is limited, *methane* gas will be created instead of water. Figure 15 illustrates the breakdown of energy and carbon from the glucose molecule depending on the oxygen availability. The two methods differ in numerous aspects, but a significant difference is the substantial energy stored within the methane gas generated during biogas production.

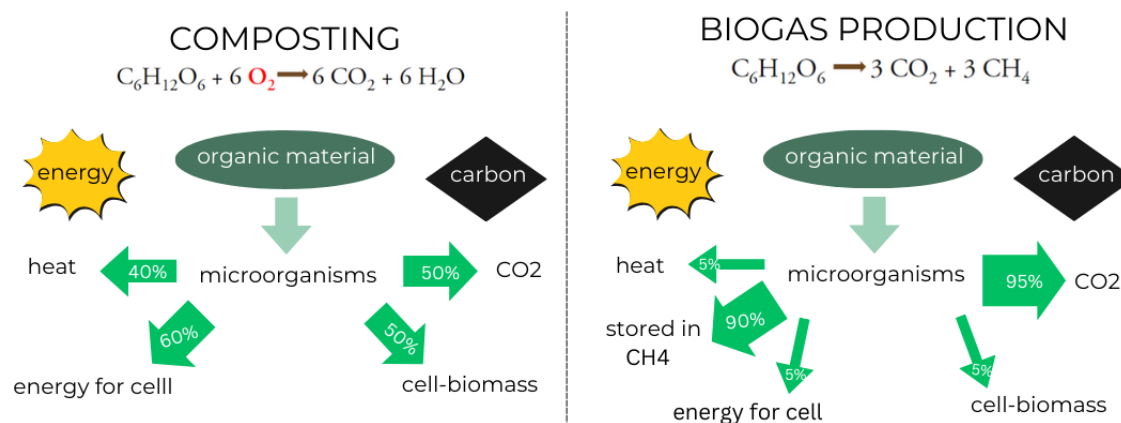


Figure 15: Composting compared to biogas production (Based on Björnsson (2023))

The composition of biowaste helps determine the most suitable biological treatment method. One key attribute is the amount of dry matter. A dry matter content of 40-50% is preferred for composting, while a lower value is desirable for the process of AD, ideally a material that is easily pumpable. The biowaste serving as the feedstock to the biogas plant should also be of higher quality, free from larger particles and pollutants, and consisting primarily of biodegradable compounds (Björnsson 2023). Lastly, a significant distinction between the two processes is the nitrogen (N) content. Composting requires a low carbon-to-nitrogen ratio (C:N), whereas a wider interval is acceptable for AD, with a recommended C:N ratio of 10-30:1, and an optimum around 16-25:1 (Vögeli et al. 2014).

Composting, is characterized by its low-cost, low-tech nature, effectively stabilizing waste and reducing its volume while also creating biofertilizer (Björnsson 2023). Resulting compost contains valuable phosphorus (P) and organic matter. However, it requires significant land area for active aeration to prevent GHG emissions such as methane and nitrous oxide. Drawbacks include the loss of energy and nitrogen from the waste, along the risk of GHG emissions.

In contrast, AD involves an advanced microbial process that can be implemented through relatively simple technology. Its system complexities include pretreatment, gas handling and upgrading. The energy present in the waste is harnessed by capturing the methane gas. Furthermore, AD also facilitates nutrient cycling, yielding a nutrient rich digestate consisting of both phosphorus and nitrogen, while also stabilizing waste and reducing its volume. The primary challenges for biogas production include ensuring waste purity to make digestate attractive to farmers for closing nutrient cycles, as well as minimizing methane leakage.

### Ecological and Social Sustainability

Community-based biogas systems connected to households offer a great deal of advantages, a topic widely explored in numerous articles and forums. Biogas replaces conventional cooking fuels with clean and sustainable energy, minimizing pressure on local wood resources and

reducing greenhouse gas emissions. When the dependence on charcoal is diminished, it leads to decreased expenditure on firewood and chemical fertilizers, while also relieving the burden of firewood collection for women and children. Instead, employment generation is increased with investments in biogas digesters. This green transition also improves indoor air quality, mitigating health risks associated with indoor smoke inhalation and respiratory illnesses (Amigun et al. 2010). Additionally, biogas systems contribute to waste management by converting organic waste into valuable energy and fertilizer, promoting environmental sustainability and enhancing agricultural productivity. In the case for the prison facility, biogas systems play a crucial role in sanitation, where managed sewage reduces health risks associated with overflowing septic tanks. By mitigating harmful odors, the systems create healthier and more livable environments (KIST 2005).

### **3.2.2 Biogas Technology**

As mentioned, biogas includes cost-effective production of both renewable energy and fertilizer with easy maintenance. Experience worldwide suggests that biogas technology is accessible and user-friendly, requiring only basic skills for construction and management. Additionally, it has been recognized as a straightforward, flexible and culturally accepted solution (Amigun et al. 2010). Human sewage, animal manure, agricultural waste as well as municipal biowaste can be utilized through the process of AD. Typically, the produced biogas consist of approximately two-thirds methane and one-third carbon dioxide. The desired component methane gas can be combusted with oxygen to generate heat as an energy source, creating carbon dioxide and water vapor as only emissions. Left is the residual product, called the digestate, serving as a biofertilizer, rich of both nitrogen (N) and phosphorous (P). This creates a closed ecological cycle and circular energy system, with a significant reduction of GHG emissions. If biowaste is left to decompose naturally, methane gas would be released, its energy potential would go unused (Björnsson 2023).

#### **Operational Parameters**

In this master's thesis, the framework for exploring the possibilities of biogas production is based in Kigali and the typical substrate feeding the digester, also called the feedstock, will be food waste from households. Technical conditions and the supervision of operational parameters are of importance, with the performance of the digester greatly influenced by the quality and quantity of the feedstock. These conditions will be analyzed and a simplified process diagram explaining the AD process is presented in Figure 16.

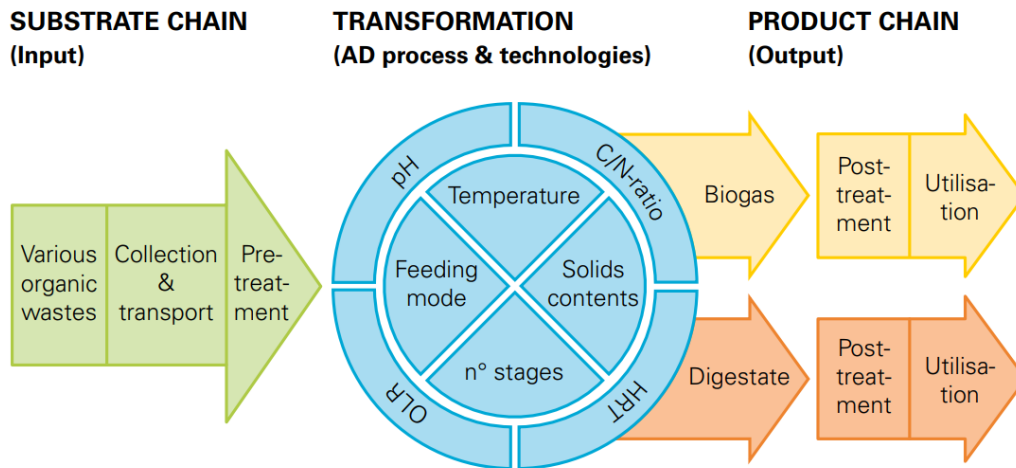


Figure 16: Simplified process diagram of AD of biowaste (Vögeli et al. 2014).

Because of Rwanda's tropical conditions and elevated altitude, there is a moderate climate throughout the year. Nighttime temperatures usually hover around 15°C, while daytime temperatures reach approximately 30°C, with little variation between seasons (Amigun et al. 2010). If studying the different microorganism active in the dome, they have ideal temperature range between 30-60°C. For a basic, community based biogas digester in a tropical climate without supplemental heating, a mesophilic temperature range (30-40°C) is more suitable than thermophilic (50-65°C), which means that mesophilic microorganisms thrive. A mesophilic system offers greater stability and resilience to fluctuations in environmental conditions than thermophilic, requiring less energy (Vögeli et al. 2014). A daily ambient temperature of at least 20°C, with a minimum temperature of 15°C is needed for the mesophilic digester (Gaddefa et al. 2006), which is the case for the typical climate in Rwanda. However, the AD process is slowed down when temperature is lower, requiring a longer hydraulic retention time (HRT) to optimize biogas production. HRT quantifies the duration that the feedstock resides within the reactor dome. For a mesophilic digester, at least 10-40 days of HRT is needed (Vögeli et al. 2014).

To create a stable AD process, an optimum pH range is 6.5-7.5. With food waste as feedstock, the pH level becomes a crucial factor due to the decomposition of vegetable oil, a biomass rich in energy, into fatty acids. Excessive amounts of these acids can lead to a reduction in pH. Hence, the utilization of oil as a substrate should be approached cautiously (Björnsson 2023). The anaerobic process is sensitive to inhibitors since some compounds can be toxic depending on its concentration. Except from oxygen, some typical inhibitors is hydrogen sulfide, organic acids, heavy metals, free ammonia, disinfectants, antibiotics and pesticides (Vögeli et al. 2014). The C:N ratio for typical household waste in Kigali is estimated to 14:1, which indicates that no nutrient supplement to the feedstock is needed according to Mucyo (2013).

The Organic Loading Rate (OLR) quantifies the biological conversion capacity of the AD system by representing the quantity of substrate introduced into the reactor volume within a specified time period. It measures the rate at which organic matter, called the total solids, is fed into the digester, influencing its performance and efficiency. For the feedstock, the

volatile solids constitute the organic matter within the total solids. This fraction contributes to the biogas production. To qualify as suitable substrate, the volatile solids should be 70-90% of the total solids. The only pretreatment needed for the feedstock is that non-biodegradable materials are extracted; although, it helps the AD process if the particle size does not exceed 5 cm (Amigun et al. 2010). These treatments can both be done manually. Ultimately, the feedstock will be mixed with equal amount of water to create an easy biodegradable slurry for the digester (Vögeli et al. 2014).

### Fixed Dome Digester

A fixed dome digester resembles an underground beehive design, constructed on a circular concrete base using clay or sand-cement bricks, see Figure 17. This closed dome-shaped structure features a feedstock inlet leading to a rigid gas-holder and thereafter a displacement pit. At the feedstock inlet various substrates such as cow dung, human sewage and kitchen waste can be fed into the digester. When the gas valve opens for utilization, gas pressure decreases, enabling slurry to flow back from the displacement pit into the digester, as depicted on the left in Figure 17. A closed outlet gas valve maintains gas pressure within the digester, pushing digestate into the displacement pit, illustrated to the right in Figure 17. As the dome is underground, the surrounding soil counteracts internal pressure fluctuations caused by gas production and usage. Additionally, the underground construction shields the digester from cold temperatures during night, ensuring a more consistent temperature (Rao et al. 2018).

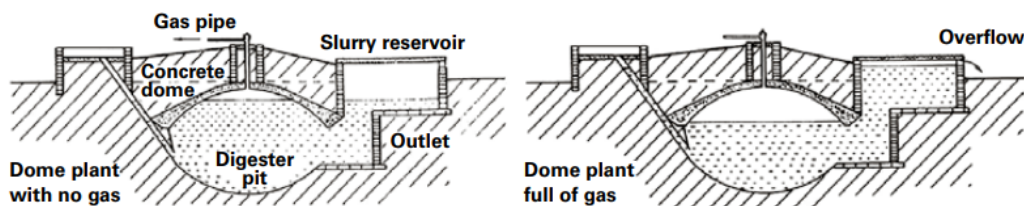


Figure 17: Fixed dome digester without (left) and with (right) gas pressure (Vögeli et al. 2014)

Fixed dome digesters vary in size, ranging from 6 to 100 m<sup>3</sup> in volume and are known for their affordability and longevity with operational lifespans of approximately 15 to 20 years. This durability is due to the use of locally sourced and cost-effective materials, as well as no moving or corroding components. Constructing these digesters requires skilled biogas technicians to ensure a gas-tight structure, thus minimizing the risk of gas leaks and extending the digester's lifetime as repairs are challenging once installed underground (Vögeli et al. 2014). It should also be noted that it is important to minimize the number of junctions and bends to maintain gas pressure and reduce the risk of leaks (Renwick et al. 2007).

### Operation and Maintenance

During the startup phase of the digester it is essential to inoculate it with the appropriate bacteria (Vögeli et al. 2014). Cow dung serves as an ideal inoculant due to its natural composition containing the necessary bacteria. Approximately 10% of the total active reactor volume is required for this purpose. Initially, feedstock should be gradually introduced to

allow the bacteria to acclimatize slowly during the start-up weeks. This gradual approach prevents overloading, such as experiences abrupt changes in digester conditions or when the substrate ratio exceeds the capacity of the active bacterial population. Overloading particularly impacts methanogenic bacteria, while the more resilient acidogenic bacteria continue to function and produce acids. This acidification inhibits the activity of methanogens. The addition of cow dung then enhances the buffer capacity, reducing the risk of acidification.

To maintain continuous gas production, the substrate must be measured and fed into the digester daily to sustain stable microbial activity. Additionally, regular checks and maintenance are required on a weekly or monthly basis to ensure optimal system performance. This includes inspecting gas pipes and joints for gas tightness and monitoring pH levels. A pH below 5.5 in the slurry or detection of an acidic odor from the effluent indicates an imbalanced or overloaded microbial population. For the fixed dome, no mixing is preformed in the digester (Vögeli et al. 2014).

### Utilization of Biogas and Digestate

Biogas leaving the digester is almost 100% saturated with water vapor and carries considerable levels of energy-deficient  $\text{CO}_2$ , along with varying amounts of corrosive and toxic hydrogen sulfide ( $\text{H}_2\text{S}$ ). Dewatering methods separate the condensate from the gas, typically installed at the lowest point of the pipeline. Depending on its intended application, biogas may require purification to eliminate  $\text{H}_2\text{S}$  and  $\text{CO}_2$ . If not consumed, biogas can be temporarily stored in high capacity containers for extended periods without affecting its energy content. However, biogas has a relatively low energy density, with approximately 6 kWh/m<sup>3</sup>, therefore storing uncompressed biogas requires a significant volume (ibid.). Three examples of conventional application of low-tech biogas are presented in Table 4.

Table 4: Common community-based biogas utilization methods

Method	Description
Household Cooking	Fuel in biogas stoves for cooking, substituting traditional cooking fuels like charcoal or Liquefied Petroleum Gas (LPG).
Heating Water	To heat water in boilers. The heated water can used for various purposes, including producing drinking water or facilitating washing, bathing and other applications.
Gas Lamp	Fuel for gas lamps, producing light through direct combustion. It mixes with air in the lamp, igniting to create a flame. This offers renewable lighting in areas with electricity constraints.

Digestate is another valuable byproduct of the anaerobic digestion process. When the digester is fed with food waste as feedstock, the resulting digestate can be safely reused as an organic fertilizer. However, if the digester is fed with human sewage, the digestate requires treatment before it can be safely reused (Rao et al. 2018).

### 3.2.3 Initiatives for Biogas Development in Rwanda

Charcoal is widely used for cooking in Rwanda due to its accessibility and cost-effectiveness. Particularly in rural and peri-urban regions, many households depend on charcoal as their primary cooking fuel. However, the widespread use of charcoal poses environmental threats including deforestation, soil erosion, and biodiversity loss. Moreover, cooking with charcoal generates indoor air pollution contributing to respiratory health issues (Kabera, Nishimwe, et al. 2016). Alternative indoor cooking methods are therefore necessary, with gas standing as a leading alternative.

In sub-Saharan Africa, domestic biogas systems are the most common but institutionally managed digesters have proven more successful (Amigun et al. 2010). The history of biogas in Rwanda dates back to the end of 1990 when the Government of Rwanda initiated efforts to promote renewable energy sources and improve access to clean cooking fuel in rural areas. Recognizing the country's vast agricultural sector and the abundance of organic waste, biogas technology emerged as a viable solution to address energy poverty and environmental challenges (Kabera, Nishimwe, et al. 2016). Since the 1990's, the Government of Rwanda has implemented various initiatives to expand biogas production across the country, targeting both urban and rural communities as well as institutions. These efforts have experienced varying degrees of success, partly due to their differences in size and function (Musabe 2024).

#### **National Domestic Biogas Program (NDBP)**

In 2007 the Government of Rwanda with support from international donors launched the *National Domestic Biogas Program* (NDBP) to develop a commercially viable and environmentally sustainable market-oriented biogas sector. The objective of the NDBP and the use of biogas included reduction of deforestation, improvement of life quality for the participants and access to an affordable renewable energy source. Managed by the Rwandan Energy Group (REG) under the authority of the Ministry of Infrastructure (MININFRA), the program aimed to construct 15 000 family-sized biogas plants by 2011. However, following a midterm review in 2009 the target was revised down to 5000 biogas plants. Recognizing the novelty of biogas technology in Rwanda, efforts were made to build capacity and transfer skills resulting in the training of over 500 masons in biogas technology. This initiative led to the establishment of approximately 40 biogas companies officially authorized by the NDBP. The NDBP has continued its efforts over the years, resulting in the installation of a total of 10 200 domestic biogas digesters in households across rural Rwanda (REG n.d.).

Since one of the main barriers in the program was the particular high upfront cost of the biogas digester, the Government of Rwanda provided subsidies with the aim to encourage the rural population to invest in them. The subsidies provided buyers with the opportunity to obtain credit from a bank or Savings and Credit Cooperative (SACCO) (Enea Consulting 2016). The entire subsidy mechanism is illustrated in Figure 18.

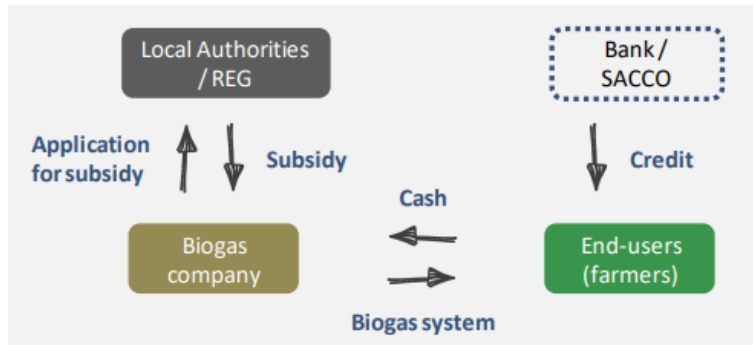


Figure 18: Subsidy mechanism of Rwanda’s NDBP (Enea Consulting 2016).

The selection criteria for households to participate in the NDBP require them to have a minimum of two cows and a willingness to own a biogas plant. The biogas system is typically a fixed dome design - an underground dome-shaped digester, but above ground flexi plants occur as well. Once installed, the biogas plant is maintained and fed by the participating family themselves. The primary substrate used in the biogas production process is a mixture of cow dung and water. On average the operational biogas units with a size range of 4-6 m<sup>3</sup> deliver approximately 2.6 hours of biogas per day, which is utilized for cooking and heating water. This output is based on an average feed quantity of 35 kg per day (Kabera, Nishimwe, et al. 2016).

### Large-scale Biogas Plants in Prisons

As part of Government of Rwanda’s broader efforts to promote biogas utilization, the Kigali Institute of Science, Technology and Management (KIST) undertook the development and installation of large-scale biogas plants in Rwandan prisons. These plants are designed to process sewage disposal together with cow dung and produce biogas for cooking purposes. The prisons generally house around 5000 inmates, mainly Rwandans convicted for their involvement in the country’s 1994 genocide. The densely living situation poses challenges for sewage disposal, presenting significant health hazards for both the prisoners and the surrounding area. The prisons are supplied with multiple underground fixed dome digesters, usually 3-5 x 100 m<sup>3</sup>, removing both smell and contamination of the sewage. Each dome has the capacity to produce about 50 m<sup>3</sup> of gas per day, meeting approximately half of the total cooking energy requirements in the prison (KIST 2005).

## 3.3 Prospects For Biogas in Mpazi Rehousing Project

Before presenting the Mpazi Rehousing Project and its biogas production potential, initiatives made by the Government of Rwanda regarding urban development of Kigali is described.

### 3.3.1 Urban Development of Kigali

In Kigali, informal settlements are common. This refers to a residential area where housing is constructed without formal land tenure or legal authorization from the government. Typically, these areas do not have fundamental infrastructure and services such as clean water, sanitation facilities, electricity and proper roads. Rapid urbanization, poverty or

a lack of affordable housing options can be reasons for informal settlements. Inhabitants usually construct improvisational shelters utilizing available materials. Living conditions within these settlements frequently pose notable challenges, with residents often encountering discrimination and marginalization. Furthermore, they are at greater risk of eviction, exposure to natural disasters and social unrest (Skat Consulting 2023).

To address these issues, the Government of Rwanda launched the Rwanda Urban Development Project II (RUDP II), building upon the achievements of the initial World Bank-funded RUDP I. The primary focus of RUDP I was infrastructure upgrades concerning roads, streetlights, drains and footpaths. After this, the World Bank financed RUDP II over a five year period (City of Kigali 2021). RUDP II aims to support essential investments to manage the challenges caused by increased urbanization alongside inadequate infrastructure and services in four selected informal settlements. Additionally, it seeks to enhance resilience to cope with the impacts of climate change in the city.

Aligned with RUDP II, the Government of Rwanda has initiated the PROECCO Project - Promoting Employment through Climate-responsive Construction. Funded by the Swiss Agency for Development and Cooperation (SDC) and implemented by the company Skat Consulting, this project assists City of Kigali in planning and executing the municipality's "Community Rehousing and Neighborhood Upgrading Project in Unplanned Settlements" in Nyarugenge district. One significant part of this effort is the *Mpazi Rehousing Project*, initiated in 2020 covering 4 ha in Gitega sector of Nyarugenge district. Co-managed by City of Kigali and the Ministry of Infrastructure (MININFRA), this project aims to enhance the Mpazi informal settlement by constructing housing units, asphalt roads with sidewalks, public lighting, WASH services and blue-green infrastructure (City of Kigali 2023).

The main objective of the Mpazi Rehousing Project is to develop a model that could be replicated elsewhere in Kigali. Not only have these partnerships facilitated the planning, design and implementation of the Mpazi Rehousing Project, but they have also succeeded in establishing a scalable rehousing process. This process is underpinned by the utilization of sustainable, robust and cost-effective construction materials, coupled with an efficient participatory design approach. Moreover, the pilot phase has confirmed that the model is well-suited for large-scale replication, with the potential for support from both public and private investment channels. Upgrading informal settlements brings numerous benefits. Firstly, it addresses demographic growth and the need to densify the city, given the limited land availability in Rwanda. Secondly, it enhances environmental resilience through a denser urban fabric. Thirdly, it improves residents quality of life and can stimulate economic activity in Rwanda (Skat Consulting 2023).

### **3.3.2 Rehousing Construction Process in Mpazi**

There are numerous neighborhoods consisting of informal settlements scattered in all parts of Kigali. Skat's project investment specifically targets the Mpazi neighborhood, a densely populated area spanning 4 ha which previously housed approximately 2000 residents. In this area, housing consisted mainly of one-story structures of various sizes, built without systematic planning or coordination (Uwaremwe 2024). The Mpazi Rehousing Project comprises two phases - Phase I (Model House + Block A-D) and Phase II (Block E-W), and is located in the western part of the capital, see Figure 19.

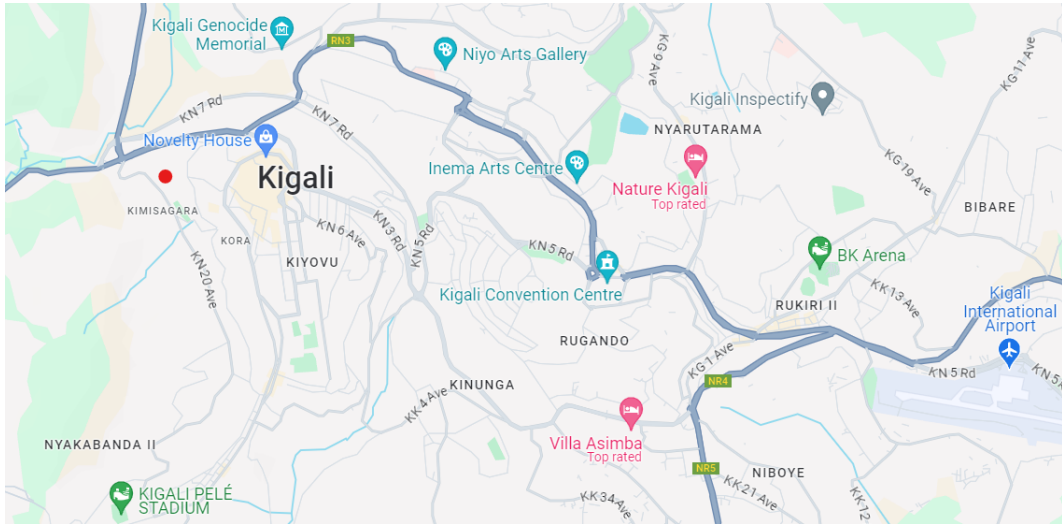


Figure 19: Map of Kigali City showing Mpazi Rehousing Project marked with red dot (Screenshot of Google Maps, 2024).

The site plan for Mpazi Rehousing Project covers 23 residential buildings, listed from Block A-W, presented in Figure 20. The plan for the site also includes a market, recreational area and development of main roads. The architectural design of the project can be seen in Figure 21. Here, an extra house is included, situated across the river. This building, known as the "Model House", serves as a pilot structure designed to evaluate materials, functionalities and the overall living conditions for residents. Today, it is housing ten families (Hagumimana 2024).

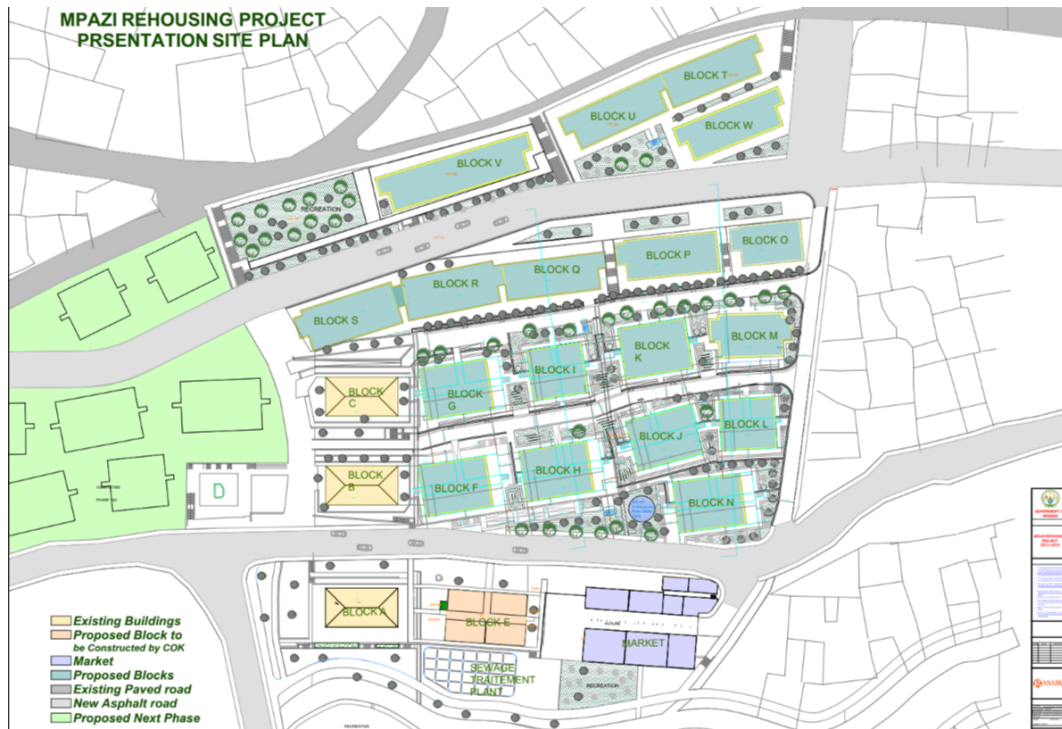


Figure 20: Site plan of Mpazi Rehousing Project (Skat Consulting, 2024).



Figure 21: Architectural design of Mpazi Rehousing Project (Skat Consulting, 2024).

### Construction of Phase I

In 2022, Phase I of the project was successfully executed. This phase involved the removal of a section of informal settlements, the construction of foundations and the completion of the first five buildings, including the Model House and Blocks A-D. These five houses can be seen in Figure 22, alongside the ongoing construction process. Transitioning to Phase II, additional informal settlements have been cleared and new foundations are prepared to

build the remaining 19 blocks. It can also be noted that surrounding the construction site, informal settlements can still be spotted.



Figure 22: Removal of more informal settlements and preparing the foundations of Block E-W.

### 3.3.3 Solid Waste Management in Mpazi

The active waste collection company covering Mpazi neighborhood is Undatwa Gitega, which provides their services on a weekly basis (Hagumimana 2024). In alignment with City of Kigali's objectives for the development of SWM in Kigali, Skat has planned for a solid waste collection station at each block dividing biowaste from non-biowaste, see Figure 23a. To assess the utilization and functionality of the collection stations, they have only been implemented at the Model House. Currently ten families live there, with typical family sizes ranging from five to eight members (ibid.).

The families living in the Model House are currently using the two containers and, according to residents in the house, they also try to separate the biowaste. Despite this investment, waste is still being accumulated at the street for weekly collection by the waste collection trucks. From the site visit at Mpazi neighborhood some organizational issues were observed at the Model House. Firstly, the waste collection station is situated in the backyard of the house, elevated on a two-meter-high concrete platform, creating accessibility challenges for waste collection workers. Secondly, the two waste containers require manual emptying, a task that seems challenging due to the absence of both waste bags and a mechanism to fully open the compartments. Thirdly, the containers appear inadequate to accommodate the waste generated by ten families.

The result from the SWM testing site at the Model House is still being evaluated. Therefore, waste collection stations have not been implemented at the blocks. Today, residents haphazardly store their solid waste around their block and then manually bring their waste bags to the street for its weekly collection. Figure 23b depicts how solid waste is deposited around the block today.



(a) Solid waste collection at the Model House consisting of two containers, one for biowaste and one for non biowaste.



(b) Current solutions for waste storage. The figure also shows the traditional cooking with charcoal outdoors.

Figure 23: Current solid waste practices in Mpazi

### 3.3.4 Cooking Practices and Biogas Conditions in Mpazi

Figure 24 shows Vestine Umutesi, who is responsible for a community consisting of 36 families in Mpazi, outside her apartment. Her responsibilities include community connections and serving as a link between residents and local authorities, ensuring the well-being of the neighborhood. Outside her home, she uses a charcoal stove for cooking beans and cassava roots that require long boiling times, see Figure 23b. For other preparations needing heat she uses LPG (Umutesi 2024). This practice was also confirmed by Teresi Mukabideri, another resident of Block A, who uses a gas container of six liters for cooking, see Figure 25. Both women expressed a positive attitude towards the use of biogas for cooking. They mentioned that while LPG is expensive, they would be open to a more cost-effective option like biogas, which they believe the community would accept as well (Umutesi 2024; Mukabideri 2024).



Figure 24: Vestine Umutesi in front of her apartment in Block A.



Figure 25: A Liquefied Petroleum Gas (LPG) container used for cooking indoors.

### 3.3.5 Village-scale Fixed Dome Biogas Digester in Mpazi

For the possibility of implementation of a biogas digester in Mpazi neighborhood, some onsite conditions and challenges need to be studied. As mentioned in the previous chapter about biogas, weather conditions and the attributes for this site make it suitable for a mesophilic digester. The waste serving as the feedstock for the digester consists solely of domestic food waste, with the majority being vegetable peelings (Mucyo 2013). A problem when using food waste as substrate is that high levels of oil or salt can be detrimental to the microorganisms. Therefore, these components need to be fed into the digester with caution (Musabe 2024). The chosen fixed dome design is motivated by its status as the most common biogas digester design in Rwanda. Additionally, its underground placement is advantageous in a densely populated area like Mpazi, as it does not take up valuable surface space. The following sections of this chapter will present the results of estimating the number of residents in Mpazi, as well as the biogas potential and the investment cost of the digester. Furthermore, an estimated cost of energy will be provided for both the produced biogas and the comparable cooking gas LPG.

#### Estimation of Residents in Mpazi

The calculated number of residents is based on data provided by Skat Consulting from Phase I and II, see Figure 26. The data provided includes type, size and number of units in each block, along with number of residents per unit. The estimation of the maximum capacity of residents in the Mpazi neighborhood (Scenario I) resulted in approximately 2900 residents, while at 85% capacity (Scenario II), it resulted in approximately 2480 residents.

<b>PHASE I: Block A-D + Model house</b>					<b>Calculations</b>	
<b>Block</b>	<b>Total living area of the block (m2)</b>			<b>Scenario I</b>	<b>Scenario II</b>	
A	775			86	73	
B	801			89	76	
C	794			88	75	
D	397			44	37	
Model house	630			70	60	
<i>Subtotal</i>	<i>2767</i>			<i>377</i>	<i>321</i>	
<b>PHASE II: Block E-W</b>						
<b>N°</b>	<b>Type of Unit</b>	<b>Unit size (m2)</b>	<b>N° of units</b>	<b>N° residents per unit</b>	<b>Scenario I</b>	<b>Scenario II</b>
1	Large Shop	35	9	4	35	30
2	Medium Shop	26	2	3	6	5
3	Small shop	15	12	2	20	17
4	Small shop	10	13	1	14	12
5	Large Studio	35	61	4	237	202
6	Medium Studio	26	87	3	251	214
7	Small Studio	15	49	2	82	69
8	Small Studio	10	11	1	12	10
9	1 Bedroom Unit	37	38	4	156	133
10	1 Bedroom Unit	20	0	2	0	0
11	1 Bedroom Unit	27	128	3	383	325
12	1 Bedroom Unit	29	48	3	154	131
13	2 Bedroom Unit	54	41	6	246	209
14	2 Bedroom Unit	44	7	5	34	29
15	Small studio	21	16	2	37	32
16	Cohousing	14	56	2	90	76
17	Single studio	30	6	3	20	17
18	1 Bedroom Unit	40	18	4	81	68
19	2 Bedroom Unit	59	30	7	196	167
20	3 Bedroom Unit	77	56	9	481	409
<i>Subtotal</i>					<i>2535</i>	<i>2155</i>
<b>Total number of residents</b>					<b>2913</b>	<b>2476</b>

Figure 26: Estimation of residents in Mpazi Rehousing Project.

### Estimation of Biogas Potential

The calculations and results of the biogas potential for Scenario I and Scenario II are presented in Figure 27. As outlined in the Methodology, the amount of substrate per day and the reactor volume were determined from the total generated biowaste. For Scenario I, an estimated reactor volume of 70 m<sup>3</sup> is needed, whereas for Scenario II, a reactor volume of 59 m<sup>3</sup> is required.

As for the biogas production, using literature values from Mucyo (2013), the estimated biogas production resulted in 42 m<sup>3</sup>/day for Scenario I and 36 m<sup>3</sup>/day for Scenario II.

**A-B: Generated biowaste and feedstock**

	T. Kabera (2019)	Skat (2024)		Someshekar (2014)	
Scenario	Biowaste per capita (kg/day ww)	No. residents	Total biowaste Mpazi (kg/day)	Ratio water to substrate	Substrate flow rate (kg/day ww)
	M_c	n	M_tot	x,y	Q_w
S I	0,40	2913	1162	2	2324
S II	0,40	2476	988	2	1976

**C: Sizing the digester**

	Assuming 1kg=1L	S. Mucyo (2013)		
Scenario	Substrate flow rate (L/day)	Hydraulic retention time (days)	Total volume of input (m3)	Total volume of reactor (m3)
	Q_v	HRT	V_input	V_reactor
S I	2324	30	70	70
S II	1976	30	59	59

**D-E: Feedstock quality and biogas production**

	S. Mucyo (2013)		S. Mucyo (2013)		S. Mucyo (2013)		
Scenario	Total Solids	Total TS (kg/day)	Volatile Solids	Total VS (kg/day)	Gas yield (m3/kg VS)	Biogas production (m3/day)	Energy content (KWh/day)
	TS	M_TS	VS	M_VS	Y	G	E
S I	19%	221	90,12%	199	0,209	42	250
S II	19%	188	90,12%	169	0,209	35	212

Figure 27: Calculations of Biogas Potential.

**Investment Calculation**

The projected investment cost for two potential scenarios of fixed dome biogas digesters in Mpazi is presented in Table 5, with detailed calculation provided in the Appendix. For Scenario I, featuring a reactor volume of 70 m<sup>3</sup>, the estimated investment cost is roughly 10 100 USD. Meanwhile for Scenario II, with a reactor volume of 59 m<sup>3</sup>, the investment cost was estimated to be 8 600 USD.

Table 5: Summary of main costs of the fixed dome digester in USD.

Type of cost	Cost/m <sup>3</sup>	Scenario I	Scenario II
Construction material	89	6204	5273
Pipes and Fittings	17	1180	1003
Appliances	16	1135	965
Labour	23	1605	1364
<b>Total</b>	<b>145</b>	<b>10124</b>	<b>8606</b>

The estimated cost/m<sup>3</sup> of the fixed dome in Mpazi is compared with investment costs of two other reactor volumes found by Kabera, Nishimwe, et al. (2016). Their investment costs were divided by their respective reactor volumes of 4 and 6 m<sup>3</sup> in order to find the comparable cost per cubic meter, as shown in Table 6.

Table 6: Comparison of estimated investment cost for a fixed dome.

Reactor volume	Source	USD/m <sup>3</sup>
4 m <sup>3</sup> fixed dome	Kabera (2016)	231
6 m <sup>3</sup> fixed dome	Kabera (2016)	187
Fixed dome in Mpazi	Calculations	145

### Cost of Energy

If used when cooking, a biogas stove consume around 0.4 m<sup>3</sup> biogas per hour (Vögeli et al. 2014). When producing 35-42 m<sup>3</sup> of biogas per day, 40-50 stoves can be used during roughly two hours every day. The calorific value of biogas is 6.0-6.5 kWh/m<sup>3</sup>. To better understand the energy content of biogas, it can be compared to other fuels commonly used for cooking and heating, see Figure 28. The cost of energy is a crucial factor when comparing different fuel sources for cooking. Consequently, an estimated cost has been calculated for the potentially produced biogas in Mpazi and compared with the estimated cost of LPG.

### Liquified Petroleum Gas (LPG)

RURA (2021)	1 RWF = 0,00077 USD	ELGAS (2024)	
Current cost	Current cost	Calorific value	Cost of Energy
RWF/kg	USD/kg	kWh/kg	USD/kWh
1260	0,970	13,6	0,071

### Biogas

	Vögeli (2014)				
Scenario	Life time	Annual cost	Daily cost	Energy content	Cost of Energy
	years	USD/year	USD/day	kWh/day	USD/kWh
S I	20	506	1,387	250	0,006
S II	20	430	1,179	212	0,006

Figure 28: Energy cost for the produced biogas and comparable cooking gas LPG.

## 4 Discussion

In this discussion complexities of the SWM in Kigali is explored, examining achievements, challenges and the potential of biogas technology as a sustainable solution. By evaluating current practices and proposing innovative approaches, we aim to offer insights and recommendations for enhancing SWM efficiency and fostering sustainable development in the city.

### 4.1 Evaluating Solid Waste Management in Kigali: Achievements and Challenges

The growing population of Kigali seems to be reflected in the ascent of the total daily solid waste generation. As shown in Table 3 in Chapter 3, the generation per capita appears to be stable while the total daily generation in Kigali has increased. However, a significant change has been observed in the collected waste - over the past decade the collection coverage of solid waste has doubled, even though the generated amount of waste has increased. The City of Kigali's efforts to improve waste collection coverage appear to have been successful.

The upcoming challenge is separating biowaste from non-biowaste. This has become the new focus for the City of Kigali, which is introducing initiatives such as public waste separation bins. Additionally, activities like the community cleaning day *Umuganda* likely influence Rwandan citizens' attitude toward waste management by promoting collective responsibility and environmental awareness. An initiative like this could be used in the future as a tool to raise citizens' awareness of the need for separating waste. There are several other strategies to promote waste separation awareness, including media campaigns, community gatherings and posters. In Rwanda, radio is more commonly used than social media, making it a particularly effective medium for raising awareness. Posters in urban areas and providing information at the community level could also serve as effective methods for raising awareness about waste separation. Furthermore, school programs are also an effective way to reach out to communities and educate children from a young age. One great advantage of operating a village-scale biogas systems at the site of the waste generation is that the biowaste is less contaminated. Separating at source increases the value of the biowaste since it is not mixed with other types of waste.

The transition from Nduba landfill, which represents an open dumpsite, to a sanitary landfill is essential for the advancement of SWM in Kigali. It is necessary for future endeavors towards a more circular and environmental friendly landfill, incorporating on-site recycling and composting at site together with risk mitigation measures. Effective management and treatment of leachate water are crucial to prevent groundwater and surface water contamination and to minimize potential environmental and public health risks associated with landfill operations. Multiple barriers have been identified in upgrading the solid waste management system in Kigali. A significant one is the lack of financial support for implementing projects aimed at advancing current systems. For instance, although substantial resources were invested in COWI's feasibility study for the development of SWM in Kigali, including plans for a sanitary landfill, there is currently insufficient funding available to implement the suggested measures. Additionally, the upgrade to a sanitary landfill requires the involvement of numerous stakeholders with interconnected responsibilities, which

further complicates and slows down the process.

## **4.2 Advancing Biogas Technology in Kigali: Key Findings**

The evaluation of community-based biogas digesters reveals several key findings. Firstly, this low-tech solution creates a closed cycle of nutrients, leading to energy savings and a decrease in GHG emissions. The use of biogas digesters enhances water quality and contributes to the conservation of both imported and national resources, such as gas and wood. Secondly, waste can become an economic benefit for households by being utilized as cooking fuel, for heating water and powering gas lamps. Thirdly, the adoption of biogas in households through initiatives like the NDBP improves livelihoods, empowers communities and fosters healthier and more sustainable environments. It benefits the role of women as they primarily oversee household waste management, cooking practices and are particularly susceptible to its health hazards. To summarize, it offers a decentralized and user-friendly method for converting waste into energy, which can reduce environmental degradation, generate economic gains and improve social conditions.

The operational parameters and design profitable for a low-tech biogas digester in Rwanda has been examined, evaluating local conditions based on literature reviews, expert interviews and site visits. The findings suggest that biogas digesters are not only suitable in rural areas of Rwanda, but in urban settings as well. A mesophilic digester appears to be the most appropriate choice, considering the country's tropical condition and moderate climate without extreme seasons. The microbial system operating at this temperature range is robust, but it will slow down the AD process somewhat and require a HRT of at least 30 days. Maintaining an optimal pH is easy if the digester is managed well, ensuring only food waste is fed, avoiding inhibitors and keeping salt and oil levels low. The typical food waste in Kigali has a high amount of volatile solids, even at surplus levels. Finally, C:N ratio of typical household waste is suitable for biogas production and fluctuations are acceptable. A community-based biogas digester enhances control over the quality and consistency of the input material, thus aiding in maintaining the quality of both biogas and digestate.

There was attempt to visit a biogas digester during the field work in Rwanda, difficulties accessing prisons and time constraints prevented this. However, similar to SWM in general, the main challenges for implementation of decentralized biogas digesters are funding, lack of knowledge for operation and maintenance along with awareness of benefits.

## **4.3 Urban Upgrade in Mpazi Rehousing Project Through Biogas Investment**

The extensive upgrade in Mpazi Rehousing Project goes beyond rehousing. Skat's aim of achieving sustainable urban development makes the project an ideal case study for investigating waste-to-energy solutions in Kigali. Today, the SWM in Mpazi is ineffective. Although plans for separation-at-source exist, they are not implemented because residents typically transfer their garbage in large bags to the street on collection day. A suggestion to Skat is to create more accessible solid waste collection stations by relocating them closer to the roads, replacing waste containers to larger, movable dumpsters. Additionally, raising awareness about waste management practices and its importance among residents of Mpazi

could help minimizing littering, reduce pollutants in the neighborhood's main water stream and enhance the area's recreational value.

The potential for implementing a biogas digester has been evaluated in terms of biogas production and investment costs. Calculations reveal that for maximum resident capacity (Scenario I), a reactor volume of 70 m<sup>3</sup> would produce 42 m<sup>3</sup> of biogas per day, while at 85% capacity (Scenario II), a 59 m<sup>3</sup> reactor would generate 35 m<sup>3</sup> daily. The estimated investment costs for these scenarios are approximately 10 100 USD and 8 600 USD, respectively. It should be noted that the investment calculation is based on prices for a fixed dome with a reactor size of 6 m<sup>2</sup> and that the assumptions presented in the Methodology was needed due to lack of up-to-date sources in Rwanda. A validation of the investment cost was made by comparing the square meter price to findings from a prior study. However, the investment cost for a fixed dome biogas digester reduces exponentially with increasing digester size. This is demonstrated by the costs presented in Kabera, Nishimwe, et al. (2016): by increasing the size by 2 m<sup>3</sup> the investment cost per cubic meter is reduced by almost 20%.

Moreover, with a calorific value of 6.0-6.5 kWh per cubic meter of biogas, the energy produced could power 40-50 stoves for approximately two hours daily. When compared to LPG, which costs 0.071 USD/kWh, biogas offers a more economical cooking fuel at 0.006 USD/kWh. According to the results, the biogas potential at Mpazi Rehousing Project appears to offer economical benefits. However, assumptions such as excluding costs of operation and maintenance and lack of up-to-date literature could negatively impact the results.

## 4.4 Conclusions

This master's thesis evaluated the potential of a waste-to-energy solution, focusing on transforming biowaste into biogas using a village-scale fixed dome digester. Waste collection coverage in Kigali reaches 88%, and the waste is transported to the semi-controlled Nduba landfill. Currently, no waste reduction method is performed and no treatment method is applied to the solid waste from households. Suitable operational parameters for the urban biogas digester were evaluated. For Mpazi Rehousing Project, a daily biogas production of 36-42 m<sup>3</sup> was estimated with an investment cost of 8 600-10 100 USD, based on findings for Scenario I and II.

The investigation revealed that Kigali, despite its clean reputation, faces significant SWM challenges such as inadequate infrastructure and informal waste disposal practices, highlighting the need for a sanitary landfill. Implementing small-scale investments like the community-based biogas digester presented could offer a more feasible and immediate solution while also paving the way for scaling up projects in Kigali. The potential integration of a biogas digester in Mpazi Rehousing Project not only align with sustainable urban development goals and already implemented national initiatives, but also presents a cost-effective solution for waste-to-energy, thereby addressing both the waste management challenges and the energy needs of the urban residents.

## 4.5 Recommendations for Future Studies

As this master's thesis was conducted within a single semester, it was faced with various limitations imposed by the time frame. However, numerous subjects within this thesis can be further studied. Primarily, there exists a significant lack of data concerning SWM in Kigali, spanning from waste generation to disposal. Additional research into the current waste characteristics and the quantity generated is needed, as existing estimates are only approximate. Hopefully, GGGI's initiative "Waste to Resources" will help contribute to the establishment of a data base of solid waste collection in Kigali.

When it comes to waste-to-energy, there are numerous viable alternatives worth studying. These include incineration, landfill gas extraction and refuse-derived fuel, co-digestion among others. Additionally, composting plays a crucial role as a waste-to-resource solution. Regarding biogas production, the importance of O&M and substrate selection should be further studied.

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