Sustainable Cassava Based Ethanol Production for Zambia

European Project Semester

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Coach: **Cynthia Söderbacka**

Team membres: **Naiara Esquinas Muñoz, Imke Wesselink, Marc Plana Villalbi**

TABLE OF CONTENTS

TABLE OF TABLES

TABLE OF GRAPHS

TABLE OF FIGURES

1. Project description

1.1 Background

As climate change continues to escalate, the world is prioritizing the switch to renewable sources of energy to mitigate the impacts of fossil fuels, the biggest source of greenhouse gas emissions.

Within this context, biofuels, particularly bioethanol, have emerged as a sustainable alternative for the transportation and energy sectors. Bioethanol is a renewable alcohol produced through the fermentation of biomass-derived sugars, which can be blended with gasoline or used as a fuel in power generation systems.

Traditionally, biogas has been produced from food crops such as corn and sugarcane, known as first-generation (1G) feedstocks. However, this practice has raised concerns about competition with food production and land use change. To address this issue, research has shifted toward utilizing agricultural residues and processing byproducts, leading to the development of so-called 1.5G biogas.

Cassava is one of the most important starch crops in tropical countries, widely used for food and industrial purposes. During the production of bioethanol from cassava, a large amount of solid residue is generated, roughly half of the total feedstock input. This residue still contains starch, cellulose, and other organic matter that still has a significant energy potential. Currently, it is mostly discarded or used as low-value animal feed, representing both an environmental challenge and a lost economic opportunity.

This project focuses on valorising this ethanol production residue through anaerobic digestion to produce biogas, which can be used as a renewable energy carrier for electricity production through combustion in turbines.

1.2 Problem Analysis

Nowadays, Zambia produces ethanol from cassava, and this process generates a larg amount of waste, around half of the original raw material. This residue has some challenges that are particularly relevant in the context of Zambia, where cassava is one of the country's major products and energy access remains unfair.

Through our project, we aim to address the situation in three different aspects: energy, by generating electricity and heat from biogas; environment, by reducing waste and emissions; and economy, by creating new value from cassava residues through biogas production.

From an environmental perspective, cassava processing generates large quantities of pulp with high wetness content, which is often discarded or left to decompose, releasing methane and contributing to greenhouse gas emissions. Converting this residue into biogas, the waste can be transformed into a valuable energy source, supporting sustainable waste management and aligning with Zambia's circular economy and climate goals.

From an energy perspective, Zambia faces a growing demand for reliable electricity while depending heavily on hydropower, which is increasingly affected by droughts and climate variability. Expanding energy sources through bioethanol-based power generation could help diversify the energy mix, promote energy security, and support rural electrification by using locally available biomass resources such as cassava pulp.

From an economic perspective, cassava is a key agricultural product in Zambia, providing income for thousands of small farmers. However, the pulp remaining after starch or flour extraction has limited

value. As emphasized by Zambia's Ministry of Agriculture, increasing cassava utilization, including biogas production, can create new market opportunities for farmers and intensify local bioenergy industries. Nonetheless, the profitability of cassava pulp-based ethanol remains sensitive to feedstock price, enzyme cost, and energy consumption during distillation and drying. Integrating energy recovery and co-product valorisation can significantly improve the economic and environmental sustainability of the process.

Therefore, the problem is not a single technical issue but a set of related challenges like underutilized agricultural residues, the need for clean and reliable electricity in Zambia, and the economic viability of renewable fuel production. To solve these issues, we need a complete approach that looks at environmental, technical, and social factors, supporting both energy transition and rural development in the Zambian context.

1.3 Objective

The objective is to determine if the wastes from cassava-based ethanol producing can be used to produce biogas, which in turn can be used to produce electricity.

Specific objectives:

- To analyse the valorisation potential of cassava residues through anaerobic digestion.
- To determine the biomethane potential (BMP) of different cassava plant fractions and their mixtures.
- To design a small-scale biogas system capable of producing electricity and heat for ethanol production.
- To estimate mass and energy balances of the integrated bioethanol–biogas system.
- To evaluate the economic and environmental benefits of using biogas in ethanol production, focusing on energy self-sufficiency and waste reduction.

System boundaries:

This study focuses on the laboratory-scale assessment of cassava residue valorisation and its integration with ethanol production. The project does not include:

- The detailed design of a full industrial-scale biogas plant or ethanol factory.

- The optimization of fermentation or distillation parameters for ethanol production.

- The complete life cycle assessment (LCA) or pilot-scale validation.

By achieving these objectives, the project will contribute to understanding how cassava waste, currently an underutilized by-product, can be transformed into a renewable energy source that supports both the ethanol production process and the broader goals of circular economy and sustainable energy in Zambia.

1.4 Stakeholders

The main stakeholders of this project are the SF-BioVac project, the local institutions in Zambia, the project coach, and our project team.

The SF-BioVac (Sustainable Futures – Biogas Value Chain for Circular Economy Competence Growth in Zambia) project provides the institutional framework for this work. It promotes cooperation between Finnish and Zambian universities in the field of bioenergy and circular economy. The partner

universities include Novia University of Applied Sciences, University of Oulu, University of Zambia (UNZA), and Copperbelt University (CBU) (SF-BioVac, 2025).

The Zambian stakeholders include local cassava farmers, the Rural Electrification Authority (REA), and industries involved in renewable energy initiatives.

Our coach, Cynthia Söderbacka, acts as an academic advisor and ensures that the project progresses according to the EPS framework and learning objectives.

Finally, the project team functions as an internal stakeholder, responsible for the research, laboratory work, process design, and coordination with all partners.

2. Project organization

2.1 Scheme

CASSAVA BIOGAS

RESEARCH

Cassava and Process Relevance
- Study cassava as an agricultural crop (production, uses, importance in Zambia).
- Identify the environmental problems caused by cassava waste and the potential for circular economy through bioethanol and biogas.

Equipment and Methods
- Study the AMPTS II system (BMP testing setup, operation principles, sensors, and gas measurement).
- Determine test conditions (temperature, inoculum-to-substrate ratio, sample preparation).
- Understand data output interpretation (CH_4 volume, cumulative curves, and process stability indicators).

Components and Materials
- Study the role of the inoculum in biogas production.
- Analyze cassava residues (pulp, peel, leaves, root).

PROCESS DESIGN AND TESTING

Laboratory
- Prepare cassava samples.
- Conduct BMP tests using the AMPTS II system.
- Analyze test results.

Theoretical Design
- Develop the process flow (pretreatment → hydrolysis → fermentation → distillation → turbine).
- Calculate mass and energy balances using data from literature and experiments.
- Identify key process parameters (conversion efficiency, biogas yield).

Modelling electricity production
- Simulate electricity generation through biogas combustion in a turbine.
- Perform sensitivity analysis on key economic and technical parameters.

REPORT

Midterm Report & Presentation
- Present project organization, risk management, and preliminary analysis.
- Explain the information from the theoretical part.
- Present work done in the laboratory.

Final Report & Presentation
- Complete all results, discussion, and conclusions from the laboratory tests.
- Show the feasibility or not of producing electricity from the biogas produced.

2.2 Gant

Task	Sep				Oct					Nov				Dec		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Study the AMPTS II system	■	■														
Determine test conditions	■	■														
Study cassava as an agricultural crop			■	■	■											
Identify the environmental problems and the potential for circular economy			■	■	■											
Analyze cassava residues				■	■	■										
Study the role of the inoculum				■	■	■										
Understand data output interpretation								■	■							
Prepare cassava samples		▨														
Conduct BMP tests			▨	▨	▨	▨	▨									
Analyze test results								▨								
Develop the process flow									▨	▨	▨					
Calculate mass and energy balances using data from literature and experiments										▨						
Identify key process parameters											▨	▨	▨			
Simulate electricity generation through biogas combustion in a turbine												▨	▨			
Analysis on key economic and technical parameters														▨	▨	

2.3 Risk management

Risk management is an essential part of project planning, since unexpected events may affect both the progress and the outcomes. In this project, risks are connected not only to the technical aspects of producing biogas from cassava pulp and its conversion into electricity, but also to the organization of the teamwork.

2.3.1 Identified Risks

Category	Risk	Probability	Impact	Mitigation strategy
Technical	Limited availability of reliable data for cassava pulp composition.	Medium	High	Use multiple sources, validate data with literature, apply conservative assumptions in calculations.
Technical	Integration of biogas with turbine model may be oversimplified.	Low	Medium	Define clear system boundaries; state assumptions transparently.
Technical / Experimental	Limited availability of cassava samples for the BMP tests. Samples are	Medium	High	Handle samples carefully, double-check experimental setup, and perform

	imported from Zambia and cannot be easily replaced if errors occur.			duplicate measurements to avoid loss of data.
Technical / Experimental	Limited availability of test equipment. The BMP machines are shared among several projects in Novia, and each test lasts about 30 days.	High	High	Plan the testing schedule in coordination with other teams; strictly follow the timetable and avoid delays in sample preparation.
Technical / Experimental	Power outage during BMP testing. Electrical interruptions may disturb long-term measurements.	Low	Medium	Monitor tests daily; ensure data is saved regularly and note interruptions in test logs. Consider backup power solutions if feasible.
Organizational	Delays in report sections due to coordination problems.	Medium	Medium	Apply project schedule (Gantt), hold weekly meetings, assign clear responsibilities.
Organizational	Communication issues in a multicultural team.	Low	Medium	Use English as common language, agree on communication tools (Teams/WhatsApp), write meeting minutes.
Organizational	Risk of uneven workload distribution.	Medium	Medium	Review task division regularly; adjust responsibilities if necessary.

2.3.2 Risk Assessment Matrix

- **High impact + high probability** → critical risks (technical data reliability, enzyme/fermentation uncertainty, ethanol cost).

- **Medium probability + medium impact** → to be monitored (team coordination, workload).

- **Low probability + high impact** → must have contingency plans (integration with turbine, environmental assessment).

2.3.3 Risk Management Plan

- **Preventive measures**: literature review to reduce technical uncertainty, continuous communication, clear Gantt chart with milestones.

- **Corrective measures**: if a technical assumption proves wrong, adapt calculations and highlight limitations; if a team delay occurs, redistribute tasks.

- **Monitoring**: risks will be reviewed in weekly meetings, and updates will be included in the project documentation.

3. About EPS and the team

3.1 About EPS

The team working on "Sustainable Cassava-based Ethanol Production for Zambia" has been formed within the framework of the European Project Semester guidelines, which stipulate that each group must include students from different countries – in this case, Spain and the Netherlands. This project also reflects the multidisciplinary nature of the team, composed of a computer engineer, an electrical and electronic engineer, and a chemist.

Both the project itself and the supporting courses aim to prepare students for the globalised work environment that most engineers face throughout their careers. This experience offers the opportunity to face the challenges that arise in a multicultural and multi-professional context, within a guided environment that facilitates the development of the necessary skills and knowledge.

Moreover, the sustainable approach for this EPS project enables the team to focus not only on ethanol production but also on the entire ecosystem surrounding cassava processing – including biogas generation from waste, renewable energy integration, and the application of circular economy principles. This broader perspective highlights the potential of cassava as a sustainable resource that can contribute to energy independence, waste reduction, and local development in Zambia.

3.2 Team members

3.2.1 Naiara Esquinas Muñoz

I am currently studying a double degree in Electrical Engineering and Electronic, Industrial and Automatic Engineering. What led me to choose these studies was my desire to improve and protect the world from an environmental perspective. Since I was a child, I knew that I wanted to dedicate my life to a project that would take care of the environment. At that time, I was not sure through which technological field I would achieve it, but shortly before starting high school my curiosity about electricity began to grow. I loved the technology classes where we built small circuits that activated LEDs and little machines.

That is how I decided to study the technological branch in high school, where I first heard about power plants and renewable energies. Then I realized that I had found a passion, a field that awakened my curiosity and, at the same time, allowed me to pursue my childhood dream: working with a technology strongly related to improving our environmental situation. For this reason, I started studying Electrical Engineering and, soon after, my curiosity and need to learn led me to Electronic Engineering as well.

When I finish my degree, I hope to study a master's in energy that will open doors for me either in the research field or in a company dedicated to energy management or to the development and implementation of renewable energy generation systems.

3.2.2 Imke Wesselink

My name is Imke Wesselink and I am studying chemistry at Saxion University of Applied Sciences in the Netherlands.

When I was in high school, I already knew I had a strong preference for science subjects like mathematics, chemistry, and physics. Initially, I wasn't sure which direction I wanted to take within these fields. After starting a part-time job in a laboratory, I knew for sure that chemistry interested me, and I decided to study it.

This project will allow me to put my lab skills and knowledge to good use, and I hope to share that with my fellow students.

3.2.3 Marc Plana Villalbí

My full name is Marc Plana Villalbí, and I am currently studying comptuer science engineering at School of Engineering of Vilanova i la Geltrú, in Spain.

Since I was a child, I have been drawn to programming, this led me to study computer engineering. Over time, I realised that computer science is much more than just coding. Is a field with an amount of challenges and opportunities to solve different types of problematics in different ways to find the most optimal solution.

My student background has allowed me to acquire a global overview of technology and its applications, and I am proud to be able to put the skills I have learned into practice to help develop this project.

3.3 Cohesion between team members

Team cohesion is one of the most important factors for the progress of the project. From the outset, thanks to the group dynamics exercises we did, which allowed us to get to know each other well, we established good channels of communication in an assertive manner. Each member of the group is contributing according to their speciality and knowledge, which allows us to approach the project from different perspectives. This diversity encourages creative problem-solving.

Roles and responsibilities were distributed according to each person's strengths, while decisions are made collectively to maintain everyone's collaboration.

Despite cultural and disciplinary differences, the team maintains a positive, collaborative, and supportive environment.

4. Methodology

4.1 Samples

The experiment uses the root, peel, pulp, leaves, and a mixture of cassava. Cellulose is also used. Cassava is a starchy root vegetable that originates from South America. It is truly valuable in rural areas as it can survive in poor, dry soils, providing food and income for small farmers. Although cassava produces many by-products such as pulp, skin, and leaves, most of them are discarded without proper treatment, causing waste and pollution. In addition, all this waste contains a large amount of carbohydrates and nutrients, so it could be used to produce biogas.[1]

Cassava pulp is the primary by-product remaining after starch is extracted from the root. It has a very high starch content (about 60—80% on a dry basis), but it contains only small amounts of protein, fiber, and minerals. Due to its composition, cassava pulp is easily broken down and can be quickly converted into sugars or methane, which helps produce early peaks of biogas.[2,3]

The peel contains much more fiber and lignin, but less starch. This means that it is more difficult to break down and takes longer to degrade. The skin also contains minerals such as potassium, magnesium, phosphorus, sodium, manganese, and zinc. In small amounts, these can help the bacteria that produce methane, but in excess they could slow down or inhibit this process.[4,5]

Cassava leaves are a nutritious food source, providing a significant amount of protein-about 29% of their dry weight. They also offer plenty of fiber, making up between 27% and 39% of their dry weight, and supply important minerals.[6–8] Inoculum is a mixture of bacteria and microbes that can ferment organic material and originates from the residual slurry of an earlier biogas production process made from waste. It starts and sustains microbial and bacterial activity.[4,9,10]

Cellulose is a complex polysaccharide which contains 3000 or more glucose units. It is the main component of plant cell walls and is therefore one of the most naturally occurring organic compounds on earth.[11] Cellulose is hard to degrade because of the bonds between the glucose units. Adding cellulose to inoculum results in a more active and stronger microbial community needed to break down difficult biomass, making the final methane yield higher and more stable. Cellulose is often used as a reference sample.[12]

4.2 AMPTS II

The AMPTS II is an automated system to determine the biochemical methane potential (BMP) of organic substrates. The process consists of three steps: the sample preparation and incubation, trapping of the CO_2 and the measuring of the methane gas. The 15 glass flasks serve as a reactor and are filled, in triplo, with a mixture of inoculum and the substrate that is tested. The determination of the inoculum-to-substrate ratio requires the prior analysis of the samples for dry residue (or moisture content) and loss on ignition (volatile solids). The reactors are placed in a water bath maintained at a constant temperature of 42 °C, and the mixture is continuously stirred to ensure homogenization. The produced biogas flows from the reactor to an individual bottle filled with NaOH and the pH-indicator thymolphthalein. The blue solution traps the CO_2 and turns colourless if the absorption capacity is running out. At the end of this filtration process, almost pure CH_4 flows through to the next unit. The volume of the gas is being measured with a wet gas volumetric measuring system. The gas flows into a flow cell that is placed in a bath filled with water. When gas flows into the cell, the cell is lifted, which gives a digital signal that is recorded. The built-in software displays the CH_4 production in graphs.[13]

4.3 Moisture content

The moisture content of a sample is determined by the total solids (TS). The total solids content reflects the percentage of a sample that remains after the water has been removed. The percentage of water removed from the original wet sample is the moisture content. A high TS value is equal to a large amount of solid material and a low water content. A low TS value is equal to a small amount of solids and a high water content. To determine the moisture content of the samples as a percentage, they are transferred to an aluminium tray and weighed. These aluminium trays are placed in an oven at a temperature of 105 °C (±5 °C) overnight. The trays are weighed. To calculate the total solids, the dried sample is divided by the sample before drying (wet sample), multiplied by 100%.[14]

$$TS[\%] = \frac{m_{dry}}{m_{wet}} * 100\%$$

- ▪ *TS[%]* - is the total solids of a sample as a percentage.
- ▪ *m_{dry}* - is the mass of the dry sample.
- ▪ *m_{wet}* - is the mass of the wet sample.

TS[%]

ROOT	75.5
PULP	60.4
PEEL	85.1
LEAVES	11.3
MIX	31.2
CELLULOSE	100
INOCULUM	4.39

Table 1. Results of the Total Solids (TS)

The results show that the cellulose is a completely dry sample, but the inoculum, leaves and mix are a very wet sample. The pulp, peel and root contain for most part of total solids.

4.4 Volatile solids

The volatile solids (VS) content represents the organic fraction of the dry matter. The volatile solids relative to the total (wet) sample indicates the fraction of VS in the original wet sample. To determine the volatile solids of the samples as a percentage, the dried samples are transferred into crucibles and placed in a muffle furnace at 550 °C for 1 hour to determine the ash content. After incineration the crucibles are being transferred to a desiccator containing a moisture-absorbing agent to cool and prevent rehydration. The samples are weighted again. To calculate the volatile solids, the burnt sample gets distracted from the dried sample and divided by the dried sample and multiplied by 100%. To calculate the total volatile solids, the burnt sample gets distracted from the dries sample and divided by the wet sample multiplied by 100%.[15]

$$VS_{TS}[\%] = \frac{m_{dry} - m_{ash}}{m_{dry}} * 100\%$$

- ▪ *VS_{TS}[%]* - is the percentage of volatile solids relative to the dry sample.
- ▪ *M_{ash}* - is the mass of the burnt sample.

$$VS_{tot}[\%] = \frac{m_{dry} - m_{ash}}{m_{wet}} * 100\%$$

- *VS_{tot}[%]* - is the percentage of volatile solids relative to original wet sample.

	VS$_{TS}$ [%]	VS$_{TOT}$ [%]
ROOT	83.00	75.42
PULP	94.79	59.69
PEEL	97.18	84.02
LEAVES	89.85	10.22
MIX	95.25	31.31
CELLULOSE	99.57	99.57
INOCULUM	70.27	3.092

Table 2. Results of the Volatile Solids and the total Volatile Solids

The results show that the cellulose consists almost entirely of organic materials, while the inoculum consists of only about 3% organic materials. As mentioned before in chapter 4.1, the cellulose is used as a reference sample. The VS(%) values for the inoculum and leaves are low compared to the others because these samples consisted mostly of water. The water from these various samples is not considered organic material for methane production. The values of the inoculum are important because all the samples are being mixed with inoculum, so every sample exist of substrate and inoculum. As mentioned in chapter 5.2, the inoculum is used to speed up the biogas production due to the microbes it contains.

5. Theoretical background

5.1 Ethanol production using cassava

1. **Why Cassava for Ethanol production**

   Cassava is one of the most widely used raw materials for bioethanol production, especially in tropical regions. Its roots have a high starch content (between 70—80% on a dry basis). Unlike other crops such as maize or wheat, cassava can grow in poor, dry soils, making it an economical and sustainable alternative for both small farmers and industrial producers. Another advantage is that ethanol produced from cassava does no compete directly against food, as this plant can grow in low-quality roots or surpluses that are unsuitable for human consumption. In addition, the waste generated during processing – such as husks, pulp or wastewater—can be incorporated into a circular system, using the starch-rich part for ethanol production and the rest to generate biogas or animal feed.

   From an environmental perspective, ethanol production from cassava achieves net negative greenhouse gas emissions. These results indicate that cassava is a sustainable raw material, as well as being versatile and suitable for the transition to renewable energy sources.

2. **Summary of the process**

   The conversion of cassava into ethanol is divided into four stages: pretreatment, enzymatic hydrolysis, fermentation and distillation.

   2.1 Pre-treatment and preparation:

   Fresh cassava roots are washed, peeled, and crushed to form a homogeneous paste. It is then left to rest at 60 degrees for one hour, adding small doses of liquefying enzymes to partially gelatinise the starch and improve its enzymatic degradation

   2.2 Enzymatic hydrolysis:

   In this stage, enzymes capable of degrading raw starch and transforming it into glucose under mild conditions (about 40 degrees and pg = 4) are used. After pre-treatment, up to 80% yield of starch conversion to glucose can be achieved.

   2.3 Fermentation:

   The result of the previous step is fermented with Saccharomyces cerevisiae using a single-step process (Simultaneous Saccharification and Fermentation, SSF). This integration means that hydrolysis and fermentation take place at the same time in the same reactor, thus reducing energy consumption and preventing the accumulation of sugars. Under optimal conditions (34 degrees for 72 hours), ethanol concentrations of around 80 g/L are achieved, with yields of 0.42 g ethanol/g on a pilot and industrial scale.

   2.4 Distillation and dehydration:

   Finally, the fermented broth undergoes distillation to concentrate the ethanol and then undergoes a dehydration process to obtain anhydrous ethanol (with a purity greater than 99-5%). The remaining solid and soluble by-products can be used as animal feed or transformed through anaerobic digestion to produce biogas.

5.2 Biogas production from cassava waste

Biogas production from cassava wate is a sustainable alternative for utilising all the by-products generated in the starch and ethanol industry. The root processing generates large amounts of pulp, peel, and wastewater, which are often discarded without being put to any use. However, this waste contains high amounts of easily degradable carbohydrates, making it an excellent raw material for anaerobic digestion and biogas production.

Anaerobic digestion process

Anaerobic digestion (AD) is a biological process in which microorganisms degrade organic matter in the absence of oxygen, producing a gaseous mixture composed of methane (CH_4) and carbon dioxide (CO_2). One of the most important factors is the substrate/inoculum (S/I) ratio, as it determines the stability of the system. The inoculum, which normally comes from sewage sludge or digesters in operation, provides active microorganisms and essential nutrients such as nitrogen and phosphorus. Recent studies show that an S/I ratio close to 1, under 35-40 degrees conditions, allows stable methane yields to be obtained.[9]

Advantages and limitations:

- Significantly reduces the environmental impact of organic waste disposal.
- Contributes to a circular economy by integrating ethanol process by-products into a closed energy circle

  Reduces dependence on fossil fuels by generating renewable energy locally.

However, cassava pulp has a low nitrogen content, which can cause nutritional imbalances if proper co-digestion is not carried out.

5.3 How to produce electricity with biogas (methane)

Biogas obtained from cassava waste can be converted into electricity using combined heat and power (CHP) systems, which simultaneously harness the electrical and thermal energy of the gas.

Before using, biogas must be purified to remove possible impurities such as hydrogen sulphide (H_2S) and moisture. Once clean, it is fed into internal combustion engines or gas microturbines, which convert the chemical energy of methane into electricity.

In integrated ethanol-biogas-CHP systems, such as those studied with cassava residues, this technology allows the energy from by-products to be fully exploited, reducing emissions and improving the sustainability of the process.

6. Results

6.1 Biochemical methane potential

The experiment ran for 37 days, during which the AMPTS II measured the volume of methane produced. The volume is expressed in Nml (Normal millilitres). The number of Nml was recorded daily in the software. To determine the accumulated volume of methane produced from the reactor with the sample, the value at which there is less than a 1% difference on three consecutive days is used. After the three days, the yield is too low to continue the process. The table below lists the number of days and the number of Normal millilitres of CH4 for each sample.

	DAYS	NML CH4
ROOT1	15	1820
ROOT2	14	1810
ROOT3	21	1967
PULP1	32	1931
PULP2	32	2008
PULP3	16	1561
PEEL1	22	1540
PEEL2	22	1581
PEEL3	28	1848
LEAVES1	25	1863
LEAVES2	24	1885
LEAVES3	25	1910
MIX1	23	2342
MIX2	14	2460
MIX3	14	2488
CELLULOSE1	16	2436
CELLULOSE2	25	2941
CELLULOSE3	22	2525
INOCULUM1	37	995.5
INOCULUM2	37	931.8
INOCULUM3	34	859.9

Table 3. Results of the volume CH_4 and the produced days of the samples.

The table shows a significant difference in the number of days for the pulp. Pulp 3 only has half the number of days compared to pulp 1 and pulp 2. This also affects the number of Nml of CH4 used in the calculations. However, the results from the mixed samples show the opposite. Mix 1 produced more than a 1% difference in methane for the longest number of days, while mix 2 and mix 3 only produced 14 days, even though mix 1 produced the least CH4. This demonstrates the importance of using the 1% method, as otherwise the process might be terminated prematurely.

6.2 Biochemical methane potential

To calculate the biochemical methane potential (BMP) from the measurements, the following formula is used:

$$BMP = \frac{V_S - V_B \frac{m_{IS}}{m_{IB}}}{m_{VS,sS}}$$

- *BMP* - is the normalised volume of methane produced per gram VS of substrate added (Nml/gVS)
- V_S - is the accumulated volume of methane produced from the reactor with sample (i.e., inoculum and substrate)
- V_B - is the mean value of the accumulated volume of methane produced by the three blanks (i.e., inoculum)
- m_{IS} - is the total amount of inoculum in the sample
- m_{IB} - is the total amount of inoculum in the blank
- $m_{VS,sS}$ - is the amount of organic material (i.e., volatile solids) of substrate contained in the sample bottle.[13]

BMP is expressed in normal milliliters of CH4 per gram of volatile solid. To calculate the number of normal milliliters of CH4 per gram of sample, the percentage of volatile solid in the sample must be taken into account. The following formula is used to calculate the BMP:

$$m_R = BMP * m_{VS,sS}$$

- *M_R - is the* normalised volume of methane produced per gram of substrate (Nml/g)

	NML/G	RSD
ROOT	119.2	11%
PULP	128.6	25%
PEEL	74.59	20%
LEAVES	19.73	4.2%
MIX	80.90	12%
CELLULOSE	281.1	13%
INOCULUM	2.325	6.6%

Table 4. Results of the CH₄ volume per gram and the RSD.
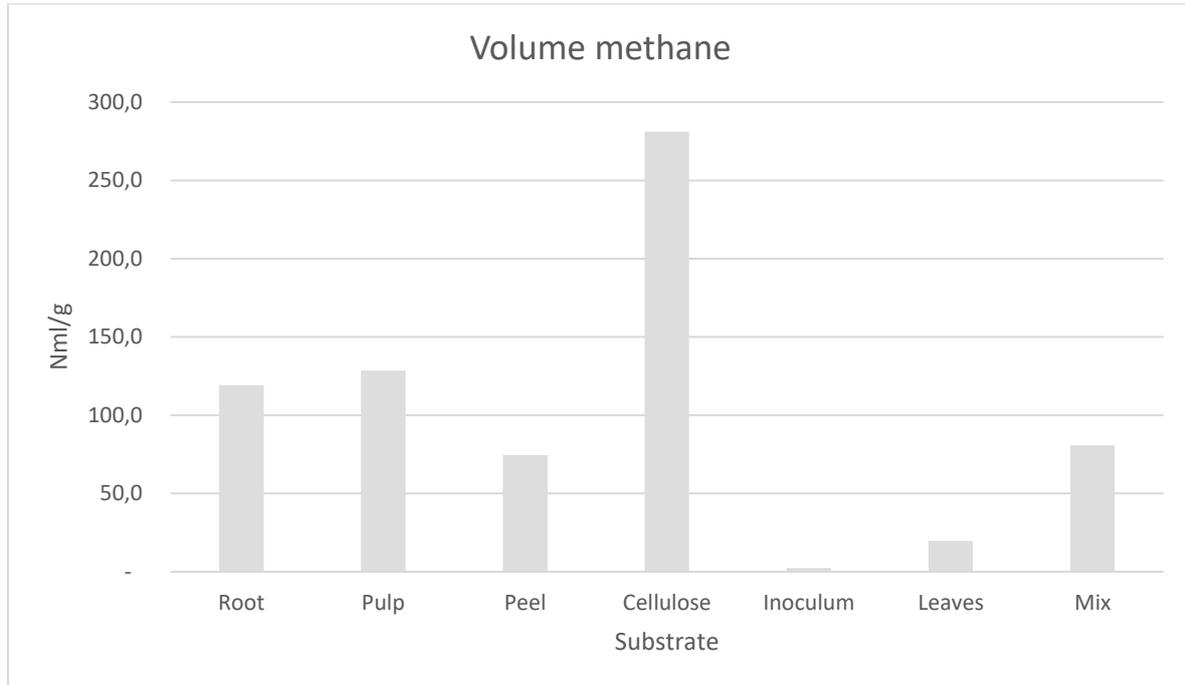
Graph 1. Results of the methane volume in Nml/g

As can be seen in the results, the cellulose yields the most normal millilitres per gram, as expected because it is the reference. The inoculum produces the least biogas, which is also expected because the inoculum is a byproduct of a biogas plant. The pulp contains the most nutrients, making it the highest-performing substrate, as the results show. Next, the root yields the highest, as the root consists largely of the pulp. The peel yields similarly to the mix. The mix produces more biogas than the leaves because it contains both leaves and root, meaning the root increases the yield.

6.3 Energy conversion

To determine the amount of energy that can be generated from the methane produced by cassava, several calculations are performed. These calculations require a few fixed values.

At first the numbers of the BMP in Nml/g are being converted to m³/g.

$$Nml/g * 10^{-6} = m^3/g$$

To calculate the energy content of biogas, the energy content of methane of 35.9-39.8 MJ/m3 is used, taking into account the high and low heating values.[16]

$$E_{biogas} = E_{methane} * V_{produced} * 1000$$

- E_{biogas} is the amount of energy produces from the biogas in MJ/kg.
- $E_{methane}$ is the energy content of methane
- $V_{produced}$ is the amount of methane volume produced in m³/g

To convert chemical energy into kilowatt-hours, the conversion factor between megajoules and kilowatt-hours is used, where 1 kWh = 3,6 MJ.[17]

$$1 \, kWh = 3.6 \, MJ$$

$$E_{kwh} = \frac{E_{biogas}}{3.6}$$

- E_{kWh} is the amount of energy in kWh/kg

The Maposa ethanol plant processes approximately 200 tons of cassava root per day, which is equivalent to 50 hectares. Of the processed cassava, approximately 0,30 tonnes/tonne of cassava peel remains, and approximately 0.40 tonnes/tonne of cassava pulp remains. This equals to approximately 0.70 tonnes/tonne root remains.[18] No data is available on how much waste there is from cassava leaves. The Maposa plant uses cassava roots for ethanol production. Assuming that cassava leaves are not processed during ethanol production, the leaves from the 50 hectares of harvested cassava would remain. Of the 50 hectares, 24% are leaves, which would amount to 63.2 tonnes of leaves per day.[19] The ratio of the mixture in the study to produce methane is 1:2 leaves:root. This amounts to a daily quantity of 189.6 tonnes, with the leaves being the limiting factor. The calculations take into account that the waste is not dried, as this is often not the case.[20]

The following formula is used to calculate the daily energy output:

$$E_{total} = E_{kWh} * m$$

- E_{total} is the total energy that can be produced per day in kWh
- m is de mass of the daily processed cassava waste in kg

The table below shows the results of the possible energy yield including the average of both energy values.

	Root	Peel	Pulp	Leaves	Mix
	(Energy Produced per day MWh)				
Tonnes Waste	140	60	80	63,2	189,6
Energy Content in Biogas (MJ/m3)					
35,9 MJ/m3(LHV)	166	44.6	103	12.4	153
39,8 MJ/m3(HHV)	184	49.5	114	13.8	170

Table 5. Results of the energy production considering the LHV and the HHV

The results show that the root can generate the most energy when the residual flows are converted into biogas methane. This table considers the Lower Heating Value (LHV) of 36.8 MJ/m3 and the Higher Heating Value (HHV) of 39.8 MJ/m3. The root and mix deliver the highest daily yield, considering the Maposa case. The mix of root and leaves can be an effective strategy for properly processing all residual flows, while also delivering substantial energy production.

7. Methods of energy conversion to electricity

The conversion of biogas into useful energy represents a key step in evaluating the feasibility of cassava-based waste valorisation systems in rural Zambia. Once biogas has been produced through the anaerobic digestion of the selected cassava fractions, it must be transformed into practical forms of energy that can support local processing needs, electrification efforts, and community services. In this project, the focus is placed on small-scale electricity generation and combined heat-and-power (CHP) production, which are particularly relevant in regions where access to stable and affordable electricity remains limited.

Biogas-to-electricity conversion can be achieved using different technologies, each with its own performance characteristics, economic implications, and suitability for rural applications. Among these, biogas-fuelled internal combustion engines and biogas-fuelled gas turbines emerge as the two most widely applicable solutions for decentralized systems. Both enable efficient utilisation of biogas while offering the possibility of recovering thermal energy, thereby increasing overall system efficiency and supporting integrated processes such as cassava drying or ethanol distillation.

This section provides a structured comparison of these two technologies. First, a technical and economic assessment of biogas engines is presented, followed by an equivalent analysis for gas turbines. Their respective efficiencies, advantages, limitations and contextual suitability for Zambia are examined using validated literature sources. Finally, a unified methodology for calculating the electrical and thermal power output from the laboratory-measured biogas yields is introduced. This methodology will be applied to the experimental results obtained in this study to quantify the energy potential of each cassava fraction and to evaluate the viability of biogas-based energy generation within the local context.

7.1 Biogas-fuelled internal combustion engines

Biogas-fuelled internal combustion engines (ICEs) are a widely used technology for small to medium-scale power generation, especially in decentralized rural contexts, which is the context of Zambia. These engines operate similarly to conventional natural gas engines but use biogas—typically composed of 50–70% methane, CO_2, water vapour, and minor impurities—as their primary fuel.[21]

Their widespread use is due to their low cost, technological maturity, and reliability, making them attractive for rural electrification, agricultural industries, and decentralized power production.[22] In a context such as Zambia, where electricity access is uneven and communities depend heavily on agricultural residues, biogas engines offer a pathway to locally produced, renewable electricity.

7.1.1 Biogas Treatment Requirements

Raw biogas cannot be used directly in internal combustion engines without prior treatment because it contains several impurities that can cause severe operational and mechanical problems. Typical contaminants include hydrogen sulphide (H_2S), siloxanes, water vapour, particulate matter, ammonia (NH_3), and variable concentrations of CO_2 and oxygen.[23] Each of these components has detrimental effects on engine operation:

- **H_2S** leads to corrosion of metallic components and forms sulphuric acid during combustion.

- **Siloxanes** are oxidised during combustion to form abrasive silica deposits on valves, pistons, and cylinder heads.

- **Moisture** causes corrosion, poor ignition quality, and freezing issues in cold climates.

- **Particles and dust** accelerate wear of pistons and cylinders.

- **CO₂** lowers the fuel's calorific value, leading to reduced power output and unstable combustion.

For these reasons, biogas destined for engine use must undergo cleaning and conditioning, typically including:

- **Desulfurisation:** Removal of H_2S through iron-oxide filters, activated carbon, biological desulfurisation units, or chemical scrubbers. This is essential to prevent corrosion and extend engine life.[24]
- **Drying / Dehumidification:** Moisture is removed using refrigeration dryers, condensation traps, or adsorption materials, ensuring stable combustion and preventing corrosion.[25]
- **Particle and Dust Filtration:** Fine filters (1–5 μm) are used to eliminate solid contaminants and protect moving engine parts from wear.
- **Siloxane Removal:** Often performed using activated carbon or molecular-sieve adsorption to avoid silica deposition inside the combustion chamber.
- **(Optional) CO₂ Reduction or Methane Enrichment:** Although not mandatory for engine use, partial upgrading can improve the lower heating value (LHV) of the fuel, resulting in higher engine efficiency and smoother operation.[21]

The extent of cleaning required depends on the engine design and operational expectations. For small-scale, rural biogas systems, a moderate purification level, chiefly H_2S removal, drying, and basic filtration, is typically sufficient and cost-effective. For long-term continuous operation, as required in integrated energy systems such as ethanol-biogas, CHP plants, a more robust gas-cleaning system is essential to ensure reliability and reduce maintenance costs.[22]

7.1.2 Working principle

Once biogas has been properly cleaned and conditioned, it can be used as a fuel in internal combustion engines. Although the thermodynamic operation of the engine remains similar to conventional gaseous-fuel engines, the combustion characteristics of biogas introduce specific behaviours that influence engine performance.

Biogas-fuelled SI engines operate according to the conventional **four-stroke Otto cycle**:

1. **Intake stroke:** a mixture of air and biogas enters the cylinder.

2. **Compression stroke:** the mixture is compressed, increasing pressure and temperature.

3. **Combustion (power) stroke:** ignition occurs via a spark plug, initiating rapid combustion.

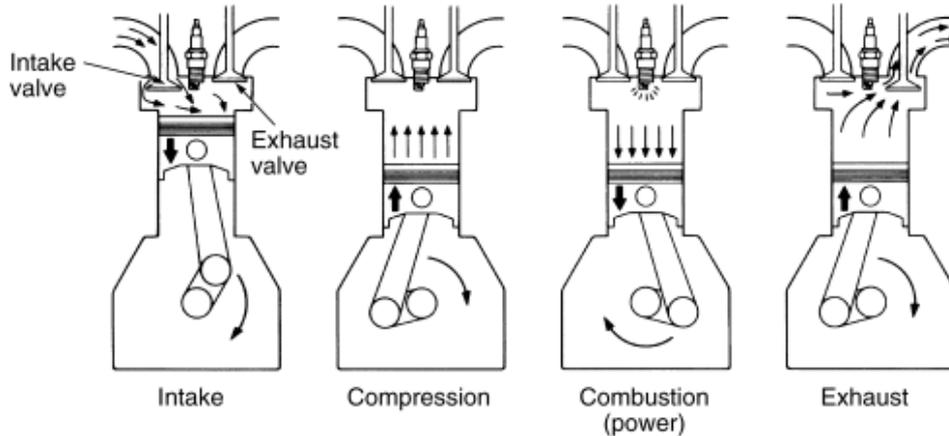4. **Exhaust stroke:** combustion products are expelled from the cylinder.

Fig 1. Four-stroke cycle[26]

The key difference when using biogas is the fuel's composition. Since biogas contains a significant fraction of non-combustible CO_2, its lower heating value (LHV) is substantially lower than that of natural gas. This leads to lower flame speed, longer combustion duration and, in some cases, increased risk of misfire if methane concentration is too low.[21] These combustion characteristics influence power output, ignition timing, mixture preparation, and thermal efficiency.

In dual-fuel configurations, a small amount of pilot diesel fuel is injected to initiate ignition, while biogas provides the majority of the energy content. This approach offers improved auto-ignition control and more robust operation in systems where biogas composition varies or methane concentration may drop.[27]

Because of these differences in combustion behaviour, engines operating on biogas generally deliver 10–30% lower power output compared to natural-gas operation unless additional modifications or optimisations are implemented. Nevertheless, when biogas quality is stable and properly conditioned, engines can achieve high reliability and efficiency in small-scale power applications.[22]

7.1.3 Economic Feasibility

Biogas engine systems are widely regarded as one of the most cost-effective technologies for converting biogas into electricity. Their economic feasibility depends mainly on capital expenditure (CAPEX), operating and maintenance (O&M) costs, biogas availability, and expected annual operating hours.

According to the International Renewable Energy Agency (IRENA), the capital cost of small-scale biogas-based power plants typically lies between 2,000 and 5,000 €/kW of installed electrical capacity, including the engine, generator, and basic gas-cleaning equipment.[28] More recent assessments for agricultural biogas plants indicate typical investment costs around 2,000–3,000 €/kW for rural-scale installations, depending on local labour, technology choice and the degree of automation.

Operating and maintenance (O&M) costs for reciprocating engines are generally expressed as a percentage of CAPEX per year. Typical values range from 5% to 10% of CAPEX annually, covering engine overhauls, oil and filter changes, spare parts, and gas-cleaning maintenance.[28] These relatively moderate O&M costs contribute to the competitiveness of biogas engines in remote areas, especially when biogas is produced from low- or zero-cost residues such as cassava waste.

The overall cost of electricity is often expressed as the levelized cost of electricity (LCOE), which distributes all investment and operating costs over the total electricity produced. Literature values for biogas engines typically fall in the range of 0.05–0.08 €/kWh when biogas is considered a zero-cost fuel.[29] For very small systems (<100 kW), the LCOE tends to be higher (around 0.10–0.17 €/kWh) due to reduced economies of scale and lower average load.

To illustrate the cost structure more transparently, a simple LCOE calculation can be performed for a representative small-scale engine. Assuming:

- a capital cost of **2,500 €/kW**,
- an economic lifetime of **10 years**,
- annual operating hours of **8,000 h/year**,
- and annual O&M costs equal to **7% of CAPEX**,

the annualised CAPEX per kWh can be approximated by dividing the specific investment by the total number of operating hours over the lifetime:

$$\text{Total lifetime hours} = 10 \text{ years} \times 8{,}000 \text{ h/year} = 80{,}000 \text{ h}$$

$$\text{CAPEX per kWh} \approx \frac{2{,}500 \text{ €/kW}}{80{,}000 \text{ kWh/kW}} = 0.031 \text{ €/kWh}$$

Similarly, the O&M cost per kWh can be estimated from the annual O&M cost divided by the yearly electricity production:

$$\text{Annual O\&M per kW} = 0.07 \times 2{,}500€ = 175€/kW \text{ per year}$$

$$O\&M \; per \; kWh = \frac{175€/kW}{8{,}000 \text{ kWh/kW}} \approx 0.022€/kWh$$

If biogas is considered a free fuel (residue-based, with no purchase cost), the simplified LCOE is then:

$$\text{LCOE} \approx 0.031 \text{ €/kWh (CAPEX)} + 0.022 \text{ €/kWh (O\&M)} \approx 0.053 \text{ €/kWh}$$

However, if biogas must be **purchased**, fuel costs must be explicitly included in the LCOE calculation. In this case, the cost of biogas is expressed per unit of chemical energy ($€/kWh_{fuel}$), while the engine produces electrical energy with a limited efficiency. Since arround **32%** of the chemical energy contained in the biogas is converted into electricity, the effective fuel cost per unit of electrical energy increases according to:

$$Fuel \; cost = \frac{\text{Biogas price } (€/kWh_{fuel})}{\eta_{el}}$$

where $\eta_{el} = 0.32$ is an average the electrical efficiency of the engine. The total levelised cost of electricity can then be expressed as:

$$\text{LCOE = CAPEX + O\&M + Fuel}$$

Fout! Verwijzingsbron niet gevonden. summarises the resulting LCOE for different biogas purchase prices.

BIOGAS PRICE (€/KWH$_{FUEL}$)	FUEL COST (€/KWH$_{EL}$)	TOTAL LCOE (€/KWH$_{EL}$)

0.00	0.000	0.053
0.02	0.062	0.116
0.05	0.156	0.209
0.10	0.313	0.366

Table 6. LOCE for different prices of biogas

For comparison, electricity generation costs from conventional alternatives in Zambia remain significantly higher. Diesel-based electricity generation in rural and off-grid areas typically ranges between 0.25 and 0.35 €/kWh, largely driven by fuel costs, transportation logistics, and price volatility. Even when grid electricity is available, effective electricity tariffs and supply costs are commonly reported in the range of 0.10 to 0.20 €/kWh, while reliability issues and outages often require complementary diesel generation. These values provide an important benchmark for assessing the economic competitiveness of biogas-based electricity systems.

The results show that even relatively low biogas prices can significantly increase the final electricity cost. When biogas is purchased at 0.02 €/kWh$_{fuel}$, the LCOE increases to approximately 0.116 €/kWh, remaining competitive with diesel-based generation. At 0.05 €/kWh$_{fuel}$, the LCOE rises to around 0.21 €/kWh, approaching typical rural diesel electricity costs. For higher biogas prices, the economic advantage of biogas engines is progressively reduced.

7.1.4 Advantages and disadvantages

Biogas-fuelled internal combustion engines present a number of strengths and limitations that directly influence their viability in small-scale electricity generation systems. Understanding these aspects is essential for evaluating whether this technology can be effectively implemented in rural or semi-industrial environments such as those found in Zambia.

Advantages

Biogas engines offer several key advantages for decentralized power production.

First, they have low capital costs compared with microturbines or fuel cells, making them financially accessible for small agricultural communities or processing plants. They are also a mature and widely deployed technology, meaning spare parts, operational knowledge and repair skills are generally easy to obtain. This is especially valuable in regions where technical support infrastructure is limited.

Another important advantage is their high operational flexibility. Biogas engines are able to respond well to changes in load and can be operated as base-load or mid-load units. When integrated as combined heat-and-power systems (CHP), they can achieve total efficiencies of 70–90%, allowing not only the production of electricity but also the recovery of thermal energy useful for cassava drying, ethanol processing, or heating needs.

Finally, engines can operate reliably at small scales (from 10–100 kW), making them particularly well suited for distributed rural systems that do not require large industrial turbines.

Disadvantages

Despite their strengths, biogas engines also exhibit certain limitations.

Their electrical efficiency, typically 25–40%, is lower than that of larger-scale power conversion technologies. In addition, because biogas contains corrosive compounds (especially H_2S and moisture), engines require regular maintenance, including oil changes, filter replacement, and periodic overhauls. If gas cleaning is insufficient, the lifespan of the engine can decrease significantly, raising long-term operating costs.

Another challenge is fuel quality variability. Because methane concentration fluctuates in anaerobic digesters depending on feedstock composition and digestion conditions, electrical output may vary unless real-time control and monitoring systems are implemented. These systems are more demanding in remote rural contexts.

Suitability for Zambia

Considering Zambia's socioeconomic context, biogas engines align well with the country's energy needs and resource availability.

Agricultural regions produce large volumes of cassava residues, which offer a stable, low-cost feedstock for biogas production. This reduces dependency on imported fuels and helps promote energy self-sufficiency in rural communities.

Biogas engines also address one of Zambia's most significant challenges: unequal and unreliable access to electricity. Many rural regions depend on diesel generators or intermittent grid supply. Engines powered by locally produced biogas can serve as stand-alone systems, mini-grid anchors, or backup units for agro-industrial facilities. Their low investment cost, simple operation, and compatibility with local mechanical skill levels make them particularly attractive for community-scale or cooperative-led energy initiatives.

Furthermore, the potential integration of thermal energy through CHP adds value to agro-processing sectors, including cassava drying, fermentation, and ethanol production. This strengthens the circular-economy approach and increases the economic return of the system.

7.1.5 Power output calculations

The purpose of the following calculations is to determine the amount of electrical and thermal energy that can be produced from the biogas obtained through the anaerobic digestion of different cassava fractions. The experimental results from the BMP/AMPTS tests provided the total biogas energy expressed directly in kW for each sample. Using these values, we can estimate the usable electrical energy generated by a biogas-fuelled engine, as well as the recoverable heat in a combined heat-and-power (CHP) configuration.

The electrical output is calculated by multiplying the biogas energy (kW) by the electrical efficiency of the motor (η_{el}); in this case, it is going to be considered a 32%.

$$E_{el} = \eta_{el} \cdot E_{biogas}$$

$$E_{el} = 0{,}32 \cdot E_{biogas}$$

If the system operates as a combined heat-and-power unit, part of the chemical energy is received as useful heat, where the thermal efficiency of the CHP recovery system (η_{th}) is going to be considered a 40%.

$$E_{th} = \eta_{th} \cdot E_{biogas}$$

$$E_{th} = 0{,}4 \cdot E_{biogas}$$

These values allow us to estimate both the power generation capability and the potential thermal integration of the biogas system within the cassava-ethanol process.

Data presentation

The energy production results obtained from biogas conversion using an internal combustion engine are summarised in **Fout! Verwijzingsbron niet gevonden.** and **Fout! Verwijzingsbron niet gevonden.**, and visually represented in Graph 2 and Graph 3. These results allow both a specific comparison per unit of waste and an absolute comparison based on the available quantities of each cassava fraction.

	ENERGY [KWH/KG]	ELECTRICAL ENERGY PRODUCED [KWH/KG]	THERMAL ENERGY PRODUCED [KWH/KG]	TOTAL ENERGY PRODUCED [KWH/KG]
ROOT	1,25	0,401	0,501	0,902
PEEL	0,78	0,251	0,314	0,565
PULP	1,35	0,433	0,541	0,974
LEAVES	0,21	0,066	0,083	0,149
MIX	0,85	0,272	0,340	0,612

Table 7. Total energy produced by the internal combustion engine per kg of waste

Fout! Verwijzingsbron niet gevonden. presents the energy produced per kilogram of waste, highlighting the intrinsic energetic potential of each cassava fraction. From a specific perspective, pulp clearly stands out as the most energy-dense substrate, producing approximately 0.974 kWh/kg of total energy, of which 0.433 kWh/kg is electrical and 0.541 kWh/kg is thermal. This superior performance is directly related to its high residual starch content and high volatile solids fraction, which favour methane production during anaerobic digestion.

Roots exhibit a similarly strong performance, reaching 0.902 kWh/kg, reflecting their high content of easily biodegradable carbohydrates. In contrast, peel and mix show intermediate values, while leaves present the lowest energy yield per kilogram (0.149 kWh/kg), due to their low volatile solids content and fibrous structure, which limits biodegradability and methane formation.
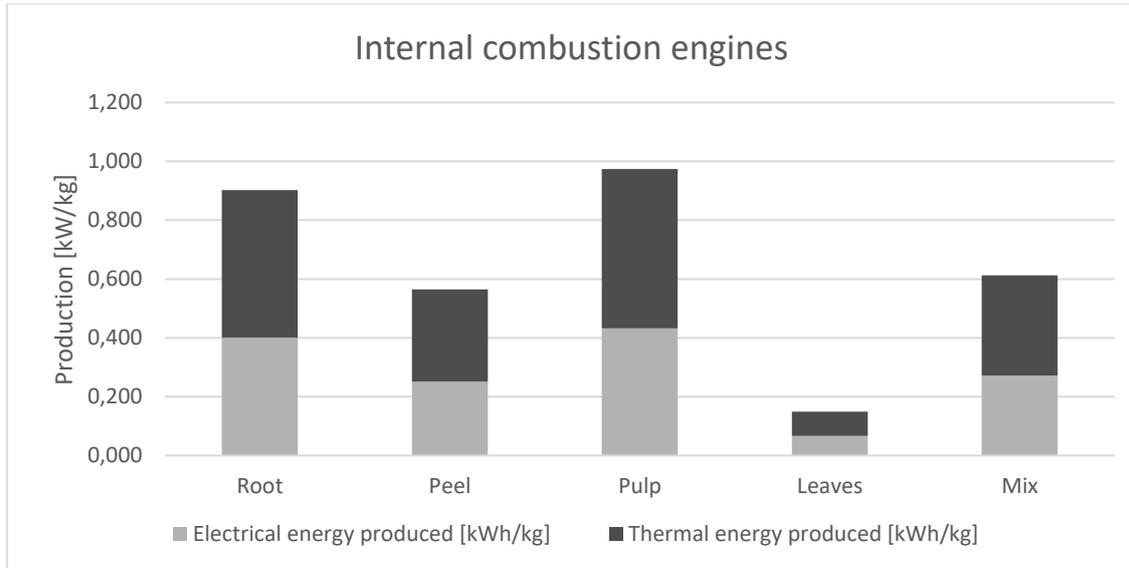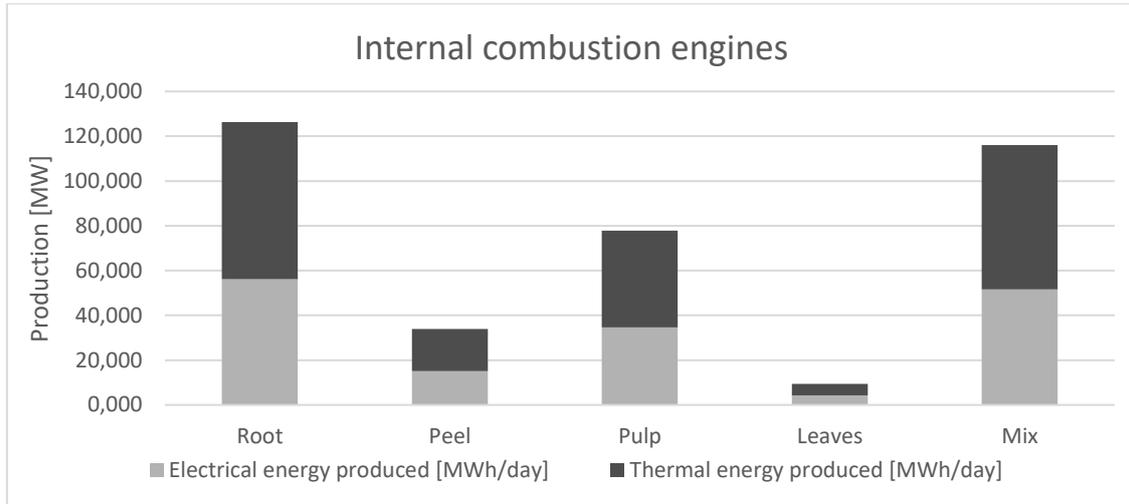
Graph 2. Results of the energy produced by the internal combustion engine per kg of waste

These trends are clearly illustrated in Graph 2 which should display a bar chart of total energy produced per kilogram (kWh/kg) for each cassava fraction (root, peel, pulp, leaves, and mix). This graph visually emphasises the superior specific energy potential of pulp and roots compared with the other fractions.

	TONNES WASTE	ENERGY [MWH/DAY]	ELECTRICAL ENERGY PRODUCED [MWH/DAY]	THERMAL ENERGY PRODUCED [MWH/DAY]	TOTAL ENERGY PRODUCED [MWH/DAY]
ROOT	140	175,44	56,141	70,176	126,317
PEEL	60	47,05	15,058	18,822	33,879
PULP	80	108,20	34,623	43,279	77,902
LEAVES	63,2	13,11	4,195	5,243	9,438
MIX	189,6	161,26	51,604	64,505	116,110

Table 8. Energy produced by the internal combustion engine

However, when the actual quantities of waste available are taken into account, the picture changes. **Fout! Verwijzingsbron niet gevonden.** shows the total energy production based on the tonnes of each fraction processed. Although pulp provides the highest energy per kilogram, the mixed fraction results in a higher overall energy production due to its substantially larger available mass (189.6 tonnes, compared to 80 tonnes of pulp). As a result, the mix generates approximately 116.1 MWh/day of total energy, exceeding the 77.9 MWh/day produced from pulp, despite its lower specific energy content.

Graph 3. Results of the energy produced by the internal combustion engine.

This effect is highlighted in Graph 3, which should present a bar chart of total energy produced (MWh/day) for each cassava fraction, incorporating the actual waste quantities. This graph demonstrates that total biogas and energy production is governed not only by substrate quality, but also by substrate availability.

Overall, these results indicate that pulp is the most efficient substrate on a per-kilogram basis, making it the optimal fraction when efficiency is prioritised. Nevertheless, from a system-level perspective, the mixed waste stream becomes highly relevant, as its greater availability compensates for its lower specific energy yield, leading to a higher total energy output. This finding underlines the importance of considering both specific energy potential and realistic feedstock availability when designing biogas-to-energy systems based on cassava residues.

7.2 Gas turbines

Gas turbines and microturbines are an alternative technology for converting biogas into electricity and heat. Although traditionally used in natural-gas and industrial power applications, smaller-scale microturbines have expanded their use in decentralized and renewable energy systems. In the context of Zambia, where rural electrification and energy diversification remain key challenges, biogas-fuelled turbines offer a technically robust and low-maintenance solution for continuous power generation, particularly when thermal energy can also be recovered.

7.2.1 Working principle

Biogas-fuelled gas turbines operate according to the **Brayton thermodynamic cycle**, where a working fluid (air) is compressed, mixed with fuel, combusted at nearly constant pressure, and then expanded to produce mechanical power. Although turbines vary in design and scale, the fundamental operation consists of the following stages:[30,31]

1. **Compression**: Ambient air enters an axial or centrifugal compressor, reaching pressure ratios typically between 3:1 and 12:1 depending on turbine size. Compression increases air density and temperature, preparing it for efficient combustion.
2. **Combustion:** Cleaned biogas (with impurities removed) is injected into the combustion chamber and mixed with compressed air. Combustion takes place at nearly constant pressure, producing high-temperature exhaust gases (≈ 850–1,100°C).[21]

3. **Expansion:** The hot gases expand through one or more turbine stages, converting thermal energy into mechanical energy. The turbine shaft drives both the compressor and the electric generator.
4. **Electricity generation:** Mechanical power is converted into electricity through a generator, producing stable AC output.
5. **Heat recovery (CHP mode):** Exhaust gas still leaves the turbine at 400–550°C, enabling heat recovery for hot water, steam, or process heating. This increases total system efficiency to 70–90%.[32]
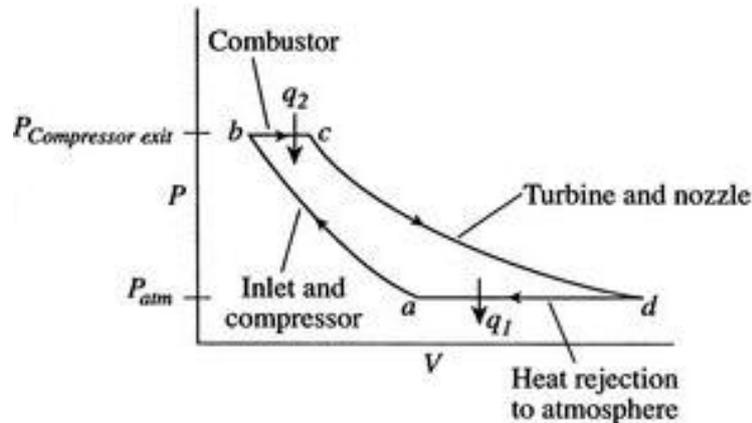
Fig 2. Brayton thermodynamic cycle[33]
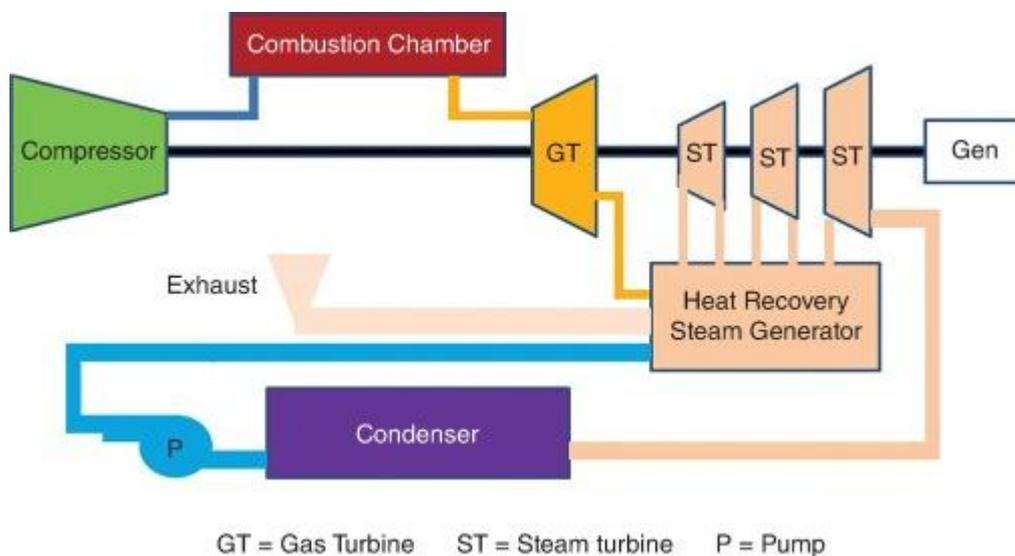
Fig 3. Turbine parts[34]

The suitability of biogas for turbine use depends strongly on its methane content and impurity levels. Turbines tolerate some variability in fuel composition but require that hydrogen sulphide, siloxanes, and particulates be removed to avoid corrosion and thermal damage.[23]

7.2.2 Economic Feasibility

The economic feasibility of biogas-fuelled gas turbines depends primarily on investment cost, efficiency performance, gas-cleaning requirements, and expected operating hours. Compared with

internal combustion engines, gas turbines typically offer lower maintenance needs and higher thermal output, but at the expense of higher capital costs and greater sensitivity to biogas quality.

According to the International Renewable Energy Agency[28], the capital cost of small-scale biogas turbine systems generally ranges between 900 and 1,500 €/kW, which is significantly higher than the investment required for reciprocating engines (IRENA, 2012). Costs tend to increase further when operated with biogas due to the need for high-quality gas-cleaning equipment, particularly siloxane removal units, which can add 10–15% to total system cost.[23] For medium-scale installations (>200 kW), industrial gas turbines achieve somewhat lower costs, typically between 700 and 1,200 €/kW, but such units exceed the scale of most rural cassava-based systems in Zambia.

Operating and maintenance (O&M) costs for microturbines are typically lower than for engines because of their simple rotor-based design and absence of pistons, bearings, and crank mechanisms. Typical annual O&M costs fall in the range of 4–7% of CAPEX, depending on gas-cleaning system maintenance and service agreements (Capstone Turbine Corporation, 2020). While mechanical wear is low, maintaining high-quality gas purification is essential to avoid turbine blade degradation, which can dramatically increase lifecycle costs.

The levelised cost of electricity (LCOE) for biogas-fuelled microturbines varies widely depending on load factor and gas quality. When operating at nominal load with clean biogas, microturbine LCOE values typically range between 0.10 and 0.18 €/kWh.[29] At lower scales (<100 kW), LCOE may rise above 0.20 €/kWh due to reduced efficiency and diminished economies of scale. In contrast, at higher scales with stable fuel supply and heat integration, microturbines can achieve competitive costs similar to small gas engines.

In the context of Zambia, the economic performance of turbines depends largely on the stability of biogas production and the existence of a continuous thermal demand. While turbines require a higher initial investment, their low maintenance needs and high-quality exhaust heat can be advantageous for integrated ethanol–biogas–CHP systems. However, for small rural installations with fluctuating biogas supply, internal combustion engines generally remain more cost-effective.

Overall, gas turbines become economically attractive only when:

- biogas production is continuous and sufficiently high,
- robust gas-cleaning systems are available,
- thermal energy recovery is integrated and valuable,
- and the installation size justifies the higher CAPEX.

For small-scale cassava-based biogas systems in Zambia, turbines may be viable in larger processing centres, but engines remain the more cost-efficient choice for community-level applications.

To illustrate the cost structure and to compare turbines and engines under equivalent conditions, the following representative parameters are assumed:

- CAPEX: **1,300 €/kW**
- Lifetime: **10 years**
- Operating hours: **8,000 h/year**
- O&M: **6% of CAPEX per year**

- Electrical efficiency: **28%**
- Biogas considered free in the base case

the annualised CAPEX per kWh can be approximated by dividing the specific investment by the total number of operating hours over the lifetime:

$$\text{Total lifetime hours} = 10 \text{ years} \times 8{,}000 \text{ h/year} = 80{,}000 \text{ h}$$

$$\text{CAPEX per kWh} \approx \frac{1{,}300 \text{ €/kW}}{80{,}000 \text{ kWh/kW}} = 0.01625 \text{ €/kWh}$$

Similarly, the O&M cost per kWh can be estimated from the annual O&M cost divided by the yearly electricity production:

$$\text{Annual O\&M per kW} = 0.06 \times 1{,}300\text{€} = 78\text{€/kW per year}$$

$$O\&M \ per \ kWh = \frac{175\text{€/kW}}{8{,}000 \text{ kWh/kW}} \approx 0.0097\text{€}/kWh$$

If biogas is considered a free fuel (residue-based, with no purchase cost), the simplified LCOE is then:

$$\text{LCOE} \approx 0.01625 \text{ €/kWh (CAPEX)} + 0.00975 \text{ €/kWh (O\&M)} \approx 0.026 \text{ €/kWh}$$

If biogas must be purchased, fuel costs must be included in the LCOE. Because only about **28% of the biogas chemical energy** is converted into electricity, the effective fuel cost per unit of electrical energy increases accordingly, amplifying the impact of biogas price on the final generation cost.

$$Fuel \ cost = \frac{\text{Biogas price } (\text{€/kWh}_{\text{fuel}})}{\eta_{el}}$$

where $\eta_{el} = 0.28$ is an average the electrical efficiency of the engine. The total levelized cost of electricity can then be expressed as:

$$\text{LCOE} = \text{CAPEX} + \text{O\&M} + \text{Fuel}$$

Table 9 summarises the resulting LCOE for different biogas purchase prices and mirrors the structure used in the engine section, enabling a direct comparison.

BIOGAS PRICE (€/KWH$_{FUEL}$)	FUEL COST (€/KWH$_{EL}$)	TOTAL LCOE (€/KWH$_{EL}$)
0.00	0.000	0.026
0.02	0.071	0.097
0.05	0.179	0.205
0.10	0.357	0.383

Table 9. LOCE for different prices of biogas

A comparison with existing electricity supply options in Zambia helps to contextualise the economic performance of biogas-fuelled gas turbines. Grid electricity, where available, typically falls within a cost range of 0.10 to 0.20 €/kWh, although supply reliability issues often affect its effective availability. These values provide a useful benchmark for assessing the competitiveness of biogas-based electricity generation.

Under favourable conditions where biogas is considered a zero-cost fuel, gas turbines achieve a very low electricity generation cost of approximately 0.026 €/kWh, clearly outperforming grid electricity. When biogas is purchased at 0.02 €/kWh$_{fuel}$, the turbine-based LCOE increases to around 0.097 €/kWh, remaining competitive with grid electricity. However, when the biogas price reaches 0.05 €/kWh$_{fuel}$ or higher, the economic advantage of turbines is significantly reduced, unless the recovered thermal energy is fully integrated into the process and adds substantial value.

From an economic standpoint, gas turbines present several strengths. Their low operating and maintenance costs, together with a simple rotating design, contribute to high reliability under continuous operation. Additionally, the availability of high-quality exhaust heat enhances the overall system value in combined heat-and-power applications, particularly in heat-intensive processes such as ethanol distillation.

7.2.3 Advantages and disadvantages

Common advantages

Gas turbines and microturbines share a number of common advantages when used to convert biogas into useful energy. First, both enable highly efficient cogeneration, as they simultaneously produce electricity and recoverable heat. This enables achieving overall efficiencies of between 70% and 90%, fully exploiting the energy potential of biogas and significantly enhancing the system's sustainability. Another favourable aspect is that they generate lower pollutant emissions compared to alternative engines, because combustion in turbines occurs continuously, homogeneously, and at high temperatures, which promotes more complete oxidation and significantly reduces the formation of NO$_x$, CO, and HC. In addition, they require less mechanical maintenance, as they do not have pistons, connecting rods, valves, or other elements subject to cyclic stress, which reduces the need for lubrication, reduces vibrations, and increases operational reliability. They also stand out for their flexibility in the use of fuels, as they can run on natural gas, biogas from anaerobic digesters, landfill gas, and even mixtures with different compositions, provided that the combustion control is properly adjusted.

Specific advantages

Despite these similarities, each technology has specific advantages. In the case of industrial-scale gas turbines, their main strength is their high-power density, which allows them to generate large amounts of electricity with relatively compact equipment. This makes them suitable for medium- and large-scale industrial plants, typically between 1 and 20 MW. They also produce exhaust gases at very high temperatures, which is especially valuable when the plant requires steam or hot air above 400 °C. This level of thermal quality favours advanced cogeneration applications. Finally, the turbines can be integrated into Brayton–Rankine combined cycles, achieving electrical efficiencies of over 45%, a figure that is difficult to match with other biogas-fired technologies.

Microturbines, on the other hand, are distinguished by their modular and extremely compact design, making them ideal for decentralized installations such as farms, small-scale digesters, agro-industrial plants, or landfills. These units can operate with low-pressure gases and fluctuating compositions thanks to their electronic control system and integrated heat recovery unit, which increases combustion stability and improves efficiency. Another characteristic feature is their quick start-up and very low noise and vibration levels, which is particularly appreciated in urban environments or pilot projects where environmental integration is a priority.

Common limitations

However, both turbines and microturbines also have common limitations. The most significant is that their electrical efficiency decreases significantly when operating below 50% of the nominal load, which requires very precise sizing based on the actual flow of biogas available. In addition, they require pre-treatment of the biogas, mainly to remove H_2S, moisture, and particles, as these contaminants can damage internal surfaces, cause corrosion, and shorten the equipment's service life. This purification system can account for between 10 and 15% of the total CAPEX. It is also important to consider that these technologies require a continuous and stable flow of fuel, so they are not suitable for intermittent or highly variable operations over time.

In terms of distinct disadvantages, gas turbines tend to have a higher initial and maintenance cost than internal combustion engines of similar power. In addition, they are more sensitive to variations in the calorific value of biogas and the presence of impurities, which requires stricter control of gas quality. On the other hand, microturbines have a slightly lower electrical efficiency, typically between 26 and 30%, compared to the 35–40% that some modern engines can achieve. Finally, because their individual power output is relatively low, if a large flow of biogas is available, it will be necessary to install multiple units in parallel, which increases the total cost of the system compared to a conventional turbine with a higher capacity.

7.2.4 Power output calculations

The aim of this calculation is to determine how much of the available biogas energy can be converted into useful electrical and thermal output when using a biogas-fuelled gas turbine. As in the previous case, the BMP/AMPTS experiments already provide the total biogas energy in kW, allowing the analysis to focus directly on the conversion performance of the selected technology. By applying the characteristic electrical and thermal efficiencies of a microturbine, we can quantify both the expected electricity generation and the amount of recoverable heat available for integration into the cassava–ethanol process.

The electrical output is calculated by multiplying the biogas energy (kW) by the electrical efficiency of the turbine (η_{el}); in this case, it is going to be considered a 28%.

$$E_{el} = \eta_{el} \cdot E_{biogas}$$

$$E_{el} = 0{,}28 \cdot E_{biogas}$$

If the system operates as a combined heat-and-power unit, part of the chemical energy is received as useful heat, where the thermal efficiency of the CHP recovery system (η_{th}) is going to be considered a 45%.

$$E_{th} = \eta_{th} \cdot E_{biogas}$$

$$E_{th} = 0{,}45 \cdot E_{biogas}$$

These values allow us to estimate both the power generation capability and the potential thermal integration of the biogas system within the cassava-ethanol process.

Data presentation

The energy production results obtained from biogas conversion using a gas turbine are presented in Table 11 and Table 11. Energy produced by the internal combustion engine, and are illustrated in Graph

4 and Graph 5. These results allow both a specific assessment of energy yield per unit of waste and an overall evaluation based on the actual quantities of cassava residues available.

	ENERGY [KWH/KG]	ELECTRICAL ENERGY PRODUCED [KWH/KG]	THERMAL ENERGY PRODUCED [KWH/KG]	TOTAL ENERGY PRODUCED [KWH/KG]
ROOT	1,25	0,351	0,564	0,915
PEEL	0,78	0,220	0,353	0,572
PULP	1,35	0,379	0,609	0,987
LEAVES	0,21	0,058	0,093	0,151
MIX	0,85	0,238	0,383	0,621

Table 10. Energy produced by the turbine per kg of waste

Fout! Verwijzingsbron niet gevonden. reports the energy produced per kilogram of waste, reflecting the intrinsic energetic potential of each cassava fraction when converted using a turbine. From this specific perspective, pulp again exhibits the highest total energy yield, reaching approximately 0.987 kWh/kg, with 0.379 kWh/kg converted into electricity and 0.609 kWh/kg recovered as thermal energy. This confirms that pulp is the most energy-dense fraction, mainly due to its high starch content and high biodegradability, which promote efficient methane production during anaerobic digestion.

Roots also show a strong performance, with a total energy yield of 0.915 kWh/kg, while peel and mix present intermediate values. As expected, leaves yield the lowest energy per kilogram (0.151 kWh/kg), owing to their low volatile solids content and fibrous composition, which limit biogas and methane generation.
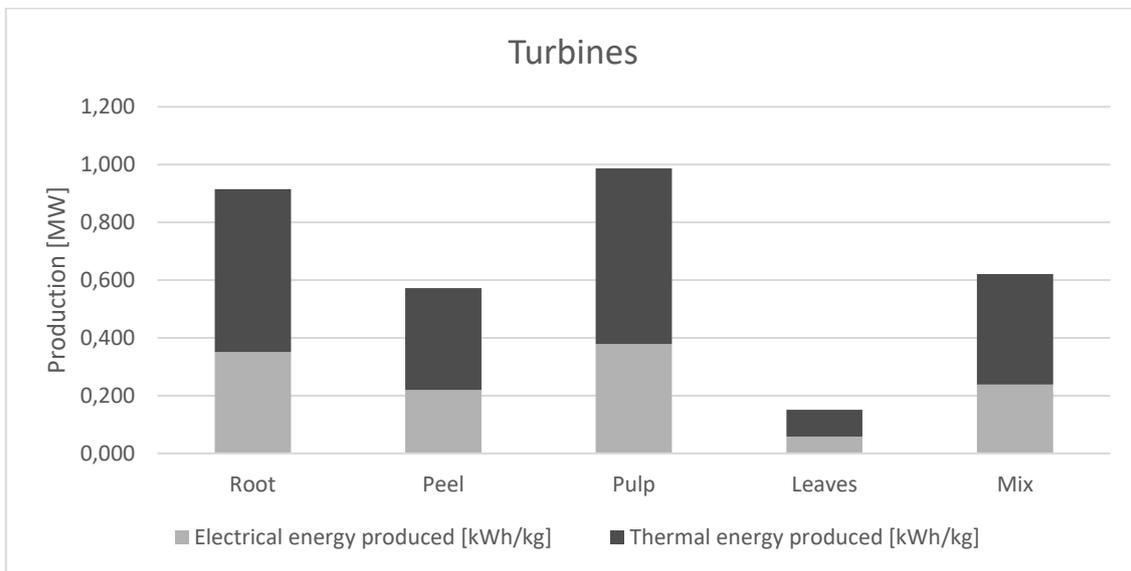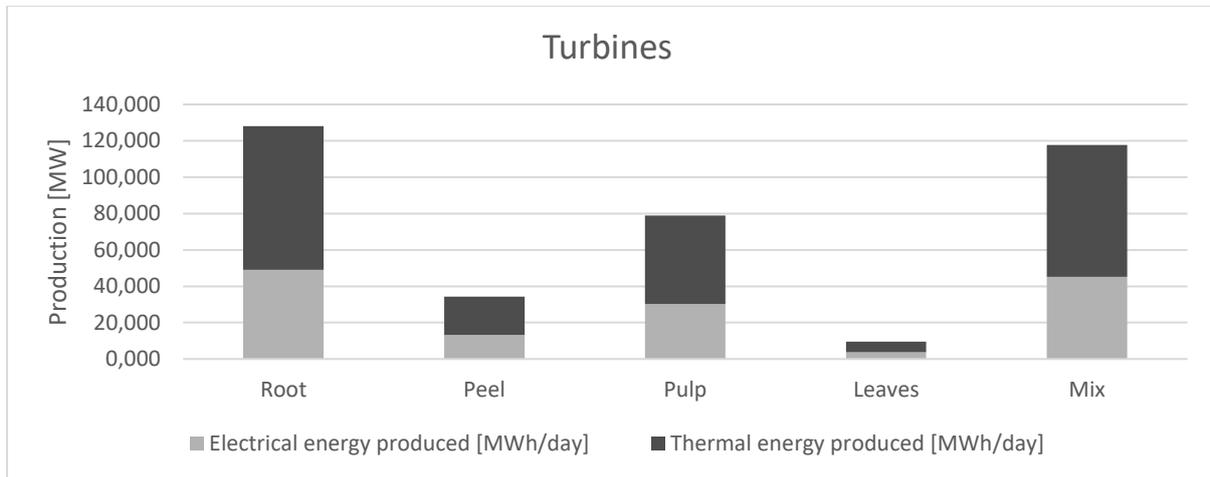

Graph 4. Results of the energy produced by the turbine per kg of waste

These trends are clearly visualised in Graph 4, which should present a bar chart of total energy produced per kilogram (kWh/kg) for each cassava fraction, highlighting the superior specific energy potential of pulp and roots when using gas turbines.

	TONNES WASTE	ENERGY [MWH/DAY]	ELECTRICAL ENERGY PRODUCED [MWH/DAY]	THERMAL ENERGY PRODUCED [MWH/DAY]	TOTAL ENERGY PRODUCED [MWH/DAY]
ROOT	140	175,44	49,123	78,948	128,071
PEEL	60	47,05	13,175	21,175	34,350
PULP	80	108,20	30,295	48,689	78,984
LEAVES	63,2	13,11	3,670	5,899	9,569
MIX	189,6	161,26	45,154	72,569	117,723

Table 11. Energy produced by the internal combustion engine

When the actual mass of waste processed is taken into account, the ranking changes. As shown in Table 11, the mixed fraction produces the highest total energy output, reaching approximately 117.7 MWh/day, despite its lower specific energy yield. This outcome is explained by the substantially larger quantity of mixed waste available (189.6 tonnes), compared with 80 tonnes of pulp, which compensates for its lower energy density.

Graph 5. Results of the energy produced by the turbine

This effect is illustrated in **Fout! Verwijzingsbron niet gevonden.**, which should display a bar chart of total energy produced (MWh/day) for each cassava fraction based on the available waste quantities. The graph demonstrates that total energy generation depends not only on substrate quality but also on feedstock availability.

Overall, these results indicate that pulp is the most efficient cassava fraction on a per-kilogram basis, making it the preferred substrate when maximising energy yield is the primary objective. However, from a system-level and practical perspective, the mixed waste stream becomes highly relevant, as its greater availability enables a higher total biogas and energy production. This reinforces the importance of combining high-quality substrates with realistic waste availability when designing turbine-based biogas-to-energy systems.

7.3 Comparative Analysis of Conversion Technologies

The next section allows a comparison between the productivity of the two main biogas-fuelled internal combustion engines and gas turbines through six graphical results. These figures show the specific energy yields, in kWh/kg, and the total daily energy production in MWh/day for thermal energy

output, electrical energy output, and overall energy output using different cassava residues: root, peel, pulp, leaves, and a mixture. Indeed, all these graphs put together give a very clear evaluation of technological performance and feedstock suitability.
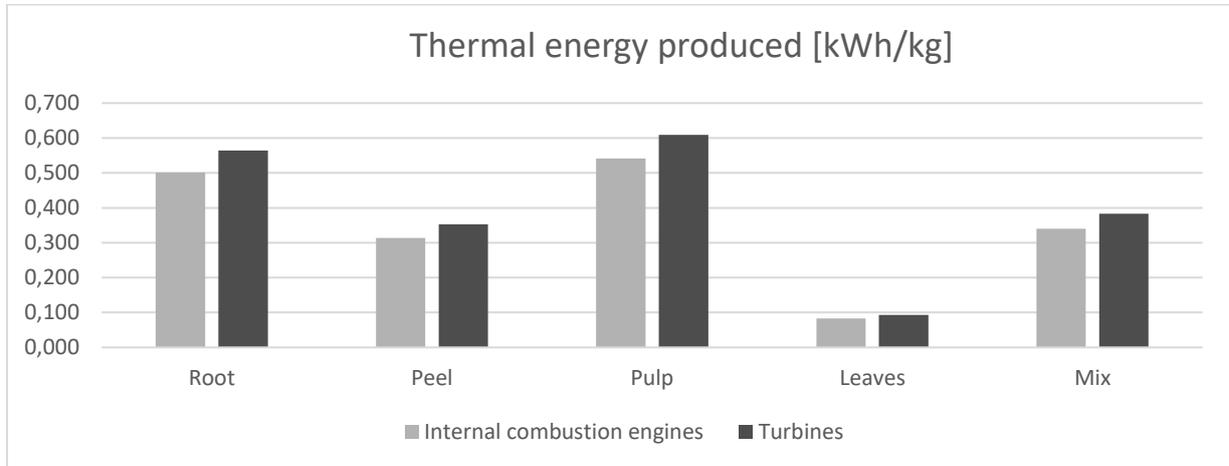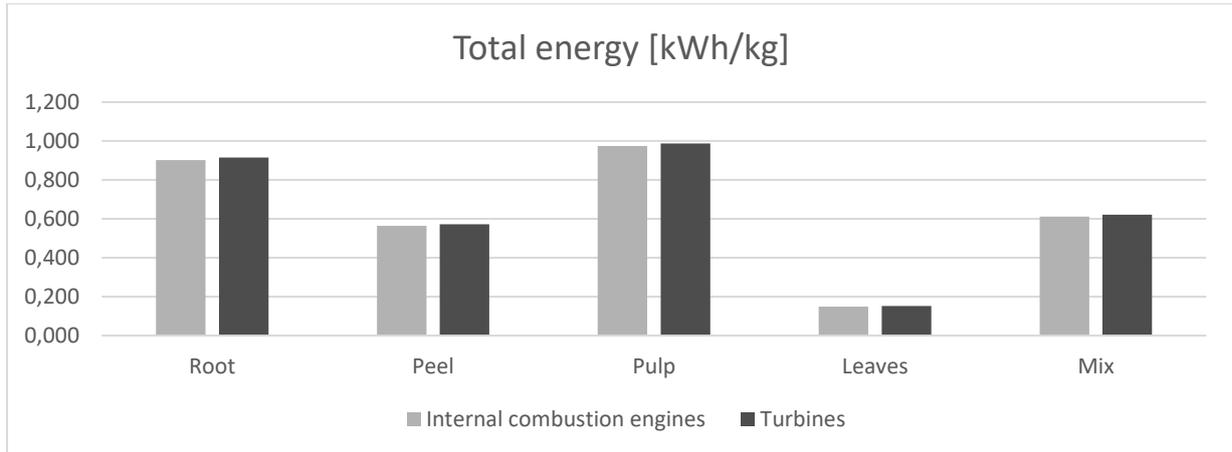

Graph 6. Thermal energy produced per kg of waste

Graph 6 shows that gas turbines always ensure a higher thermal output for a cassava fraction compared to internal combustion engines. The evidence of this trend appears particularly marked for pulp and root, where turbine-based power plants recover a greater fraction of biogas energy as useful heat. This is associated with the inherently higher thermal efficiency of turbine-required processes, like ethanol distillation or the drying process.
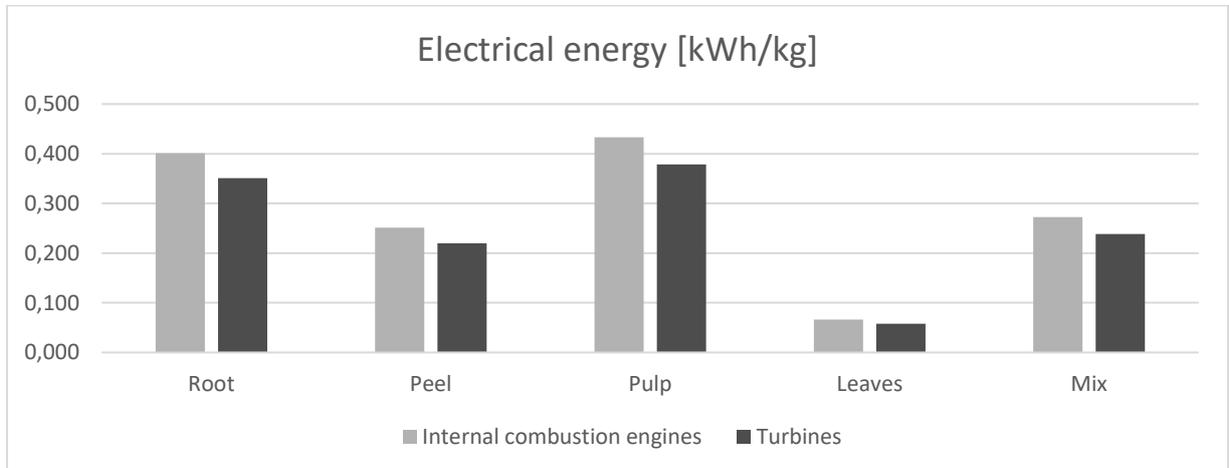

Graph 7. Electrical energy produced per kg of waste

Graph 7 shows that turbines are less efficient compared to internal combustion engines in terms of how much electrical energy is produced per kilogram of substrate; this applies to all residues and the differences are most notable for root, pulp, and the mixed substrate. The reason for this is explained by the higher electrical efficiency of engines, emphasizing their suitability when the generation of electricity is the main objective of the biogas system.

Total energy [kWh/kg]

Graph 8. Total energy produced per kg of waste

This can be seen in Fout! Verwijzingsbron niet gevonden.where both turbines and engines give very similar total specific energy yields when considering both forms of energy together. Whereas turbines convert more into heat and engines into electricity, the recovery of energy on a total basis per kilogram of substrate is similar. Thus, the selection of the technologies does not affect total energy recovery in a big way but rather a distribution between thermal and electrical output.

Thermal energy produced [MWh/day]
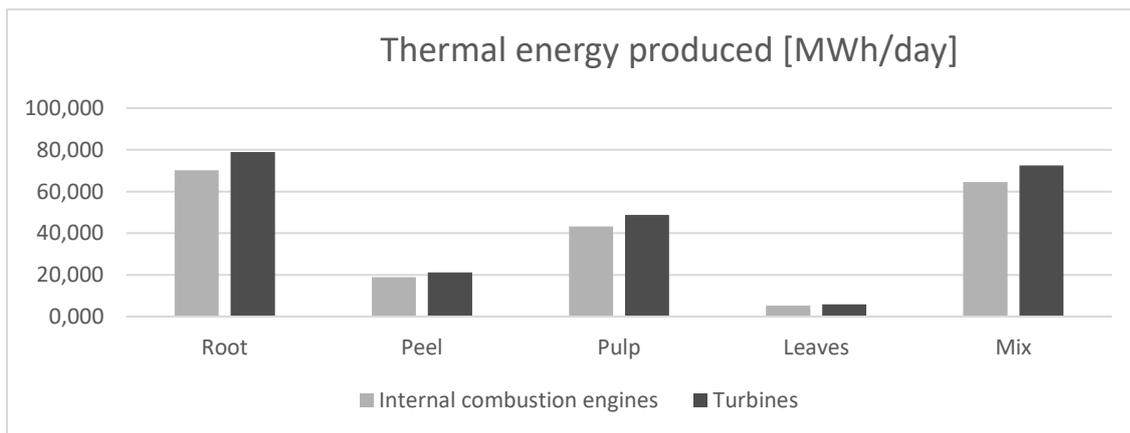
Graph 9. Thermal energy produced per day

Turning now to absolute production, Graph 9 reminds the present work once again about turbines' edge in producing heat at a system scale. Turbines would produce substantially more daily thermal energy than engines for high-availability substrates like root and pulp. Especially relevant in the context of integrated ethanol–biogas systems, this result is important, given the continuous and substantial heat demand.

Electrical energy [MWh/day]
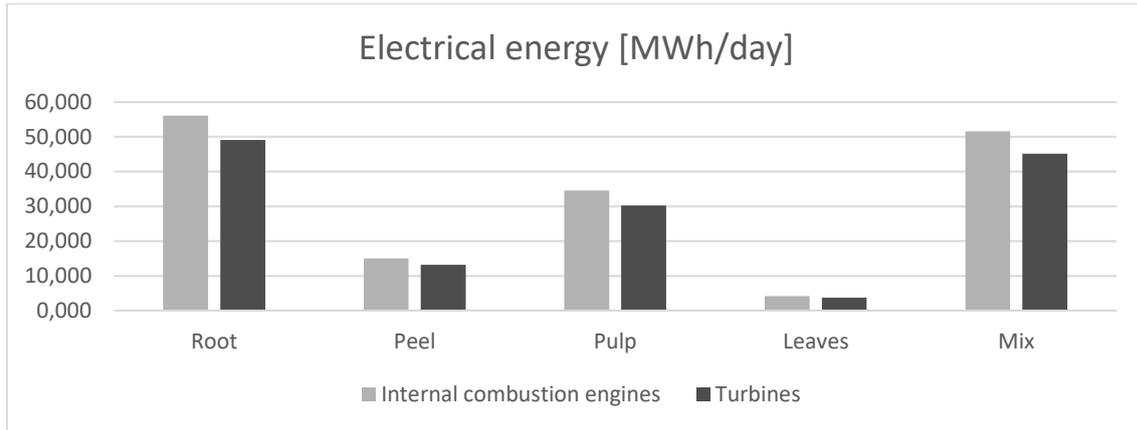
Graph 10. Electrical energy produced per day

As can be seen in Graph 10, in the case of all residues, the engines have higher daily electrical output; in terms of absolute difference, it was observed that root and pulp showed the largest differences. This confirms that the engine is particularly apt for decentralized electricity supply, rural electrification, or grid support.

Total energy [MWh/day]
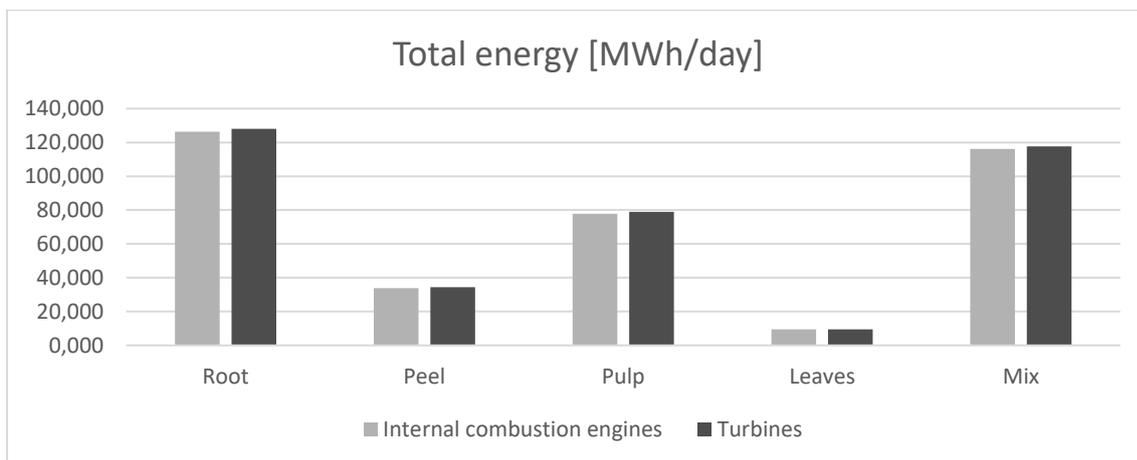
Graph 11. Total energy produced per day

Finally, Graph 11 shows the two technologies reach approximately the same total daily energy production. There are small differences depending on the substrate, but in general, the total energy potential is basically determined by biogas yield and residue availability rather than the conversion technology. That feeds back into the conclusion that the feedstock selection itself plays a big role in total energy output, whereas less dependence exists on the feedstock from either the engine or turbine.

From the feedstock point of view, cassava pulp is the most effective residue for biogas production on a per-kilogram basis, since in all graphs it shows the highest specific energy yields. However, considering real residue availability, cassava root then becomes the most favourable feedstock for energy production, since its higher mass flow leads to higher total daily energy generation.

In terms of conversion technologies, for thermal energy generation, gas turbines are preferred; instead, internal combustion engines are more efficient for electrical generation. Their choice, in this case, shall be made according to the final application: turbines are advisable when processes with high heat demand need to be served, while engines are more appropriate if electricity is the preferential

target. In integrated systems, this trade-off shall be accurately weighed in order to find the best compromise for the whole system performance and, broadly speaking, for the diffusion of circular energy use in cassava-based ethanol production.

7.4 Estimated energy demand of a Cassava ethanol plant.

Because the specific technical data of the Maposa ethanol plant are not publicly available, it is not possible to determine the exact energy requirements of that facility. For this reason, and to allow a realistic assessment of the potential contribution of our biogas system, we developed a hypothetical reference plant based on the real production of the Maposa ethanol plant, complemented with energy consumption values obtained from published scientific and industrial sources. These estimations do not represent the real plant but provide a reasonable benchmark consistent with similar cassava-to-ethanol processing facilities.

Maposa ethanol plant expected to produce 50,000 litres of ethanol per day, processing approximately 200 metric tonnes of dry cassava per day. Using these values as the production baseline, we estimated the electrical and thermal energy demand of such a facility. The estimation is grounded in two types of literature sources. First, an electricity consumption of 105 kWh per tonne of ethanol is reported for cassava-based ethanol plants[35] Applying this value to the daily ethanol output (≈39.5 tonnes/day when converting 50,000 L at 0.789 kg/L) yields an estimated electrical demand of approximately 4,142 kWh/day. This value falls within the range reported in other cassava-ethanol energy analyses.

Second, the thermal energy demand dominated by the distillation and dehydration stages was estimated using data from Reith et al., who cite an optimized heat requirement of approximately 4 MJ of process heat per litre of ethanol in modern first-generation bioethanol plants (*Co-production of bio-ethanol, electricity and heat*). Applying this figure to the plant's 50,000 L/day output results in a daily thermal demand of around 200,000 MJ/day, equivalent to roughly 55.6 MWh/day.

Based on the literature and calculations above, the reference plant used for our feasibility assessment will operate with the following energy requirements:

- **Ethanol production:** 50,000 L/day
- **Cassava processed:** 200 t/day
- **Electrical energy consumption:** ≈ **4,142 kWh/day**
- **Thermal energy consumption:** ≈ **55.6 MWh/day**

These values provide a coherent and literature-supported basis for comparing the energy demand of a cassava ethanol production system with the energy output that can be obtained from cassava residue based biogas using either an internal combustion engine or a gas turbine.

Among the cassava fractions analysed (root, peel, pulp, leaves, and a mixed sample), the pulp exhibited the highest specific energy potential in the BMP/AMPTS results. However, when the actual availability of residues is considered, the root fraction becomes the most relevant feedstock for the final feasibility assessment. Although pulp yields more energy per kilogram, the substantially larger quantity of cassava roots available results in a higher overall biogas and energy production. For this reason, the final assessment is based on the root scenario, which represents the most realistic and practically achievable performance of the biogas system.
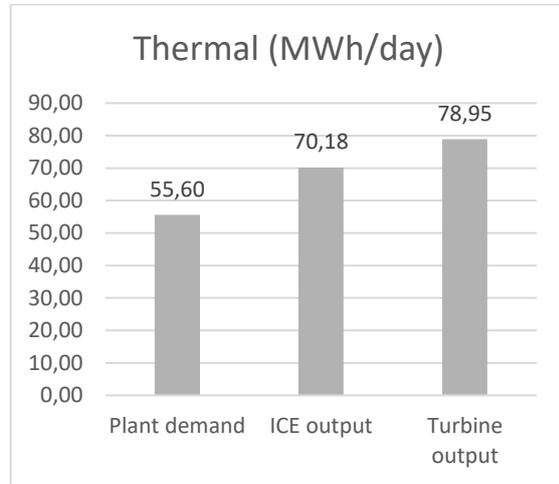
SOURCE	ELECTRICAL (MWH/DAY)	THERMAL (MWH/DAY)
PLANT DEMAND	4,14	55,60

ICE OUTPUT	56,14	70,18
TURBINE OUTPUT	49,12	78,95

Table 12. Energy provided and demanded.
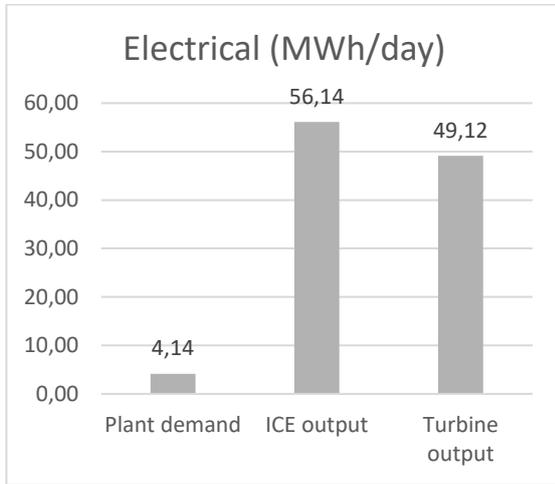
Graph 12. Electrical energy demanded vs provided

Graph 13. Thermal energy demanded vs provided

The energy produced from the root-derived biogas was compared with the estimated energy demand of the hypothetical ethanol plant, allowing a direct evaluation of whether the facility could be supplied by the biogas system. As shown in Table 12, Graph 12 and Graph 13 the contrast between plant demand and available biogas energy is significant. While the plant requires approximately 4.14 MWh/day of electricity and 55.60 MWh/day of thermal energy, the biogas obtained from cassava roots could generate 56.14 MWh/day of electricity and 70.18 MWh/day of heat when converted using an internal combustion engine.

Under the gas turbine configuration, the electrical output is slightly lower (49.12 MWh/day), but the thermal output increases to 78.95 MWh/day, which is particularly advantageous for heat-intensive stages such as ethanol distillation. In both configurations, the electrical production exceeds the plant demand by more than an order of magnitude, and the thermal production comfortably surpasses the required process heat.

These results clearly demonstrate that the biogas potential derived from cassava roots is more than sufficient to cover the full energy demand of the ethanol plant, supplying over 13 times the required electricity and providing a thermal surplus in all cases. Consequently, energy availability does not constitute a limiting factor for plant operation. This is clearly illustrated in the graphical comparison, where the bars representing both internal combustion engine and gas turbine outputs largely exceed the corresponding plant demand for electricity and heat.

Considering the specific energy profile of ethanol production, where thermal energy plays a dominant role, particularly in distillation, the gas turbine emerges as the most suitable technology for supplying the ethanol plant, due to its higher thermal output and the availability of high-quality recoverable heat. Under the assessed scenario, turbine operation not only satisfies the full thermal demand of the plant, but also generates a significant surplus of electrical energy, which can be exported to the grid where interconnection is available.

Based on the energy balance of the system, a total of 175.44 MWh/day of chemical energy is available in the produced biogas. To fully satisfy the thermal demand of the ethanol plant (55.6 MWh/day) using

a gas turbine operating with a thermal efficiency of 45%, approximately 123.56 MWh/day of biogas energy is required. This leaves a biogas surplus of about 51.9 MWh/day, which can be sold as fuel for internal combustion engines in non-electrified rural areas.

While supplying the required process heat, the turbine simultaneously generates electricity. With an electrical efficiency of 28%, the turbine produces approximately 34.6 MWh/day of electricity from the biogas used. After covering the plant's electrical demand (4.14 MWh/day), an excess of approximately 30.5 MWh/day of electricity remains available for export to the grid.

USE OF ENERGY	ENERGY (MWH/DAY)	RATE
THERMAL ENERGY USED IN ETHANOL PLANT	55.60	31.7 %
ELECTRICAL ENERGY USED IN PLANT	4.14	2.36 %
ELECTRICAL ENERGY EXPORTED TO GRID	30.46	17.37 %
BIOGAS SURPLUS SOLD	51.88	29.6 %
CONVERSION & SYSTEM LOSSES	33.36	19.0 %
TOTAL	175.44	100 %

Table 13. Biogas energy utilization
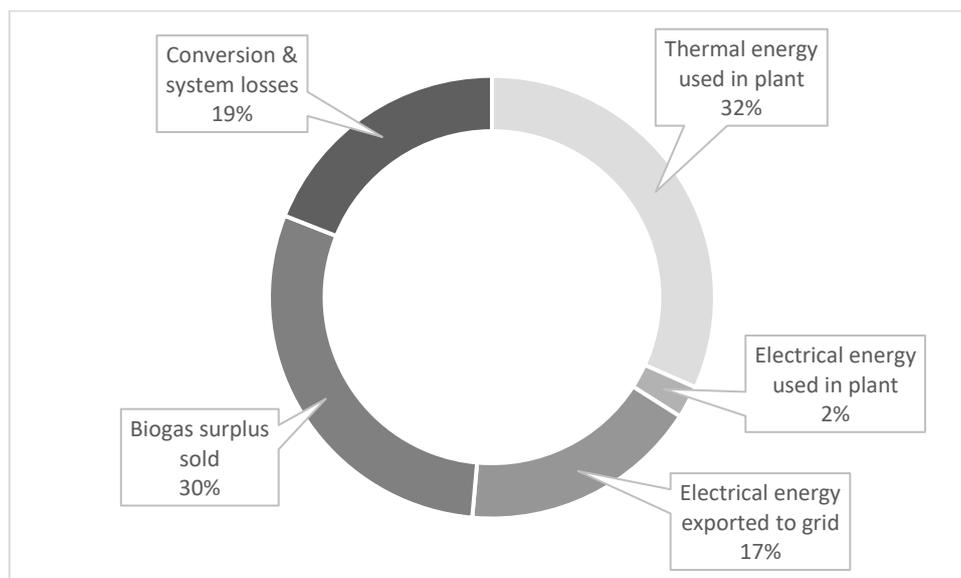
Graph 14. Biogas energy utilization

Graph 14 illustrates the distribution of the total chemical energy contained in the produced biogas once it is converted and allocated within the proposed energy system. The diagram provides a clear overview of how the available biogas energy is utilised to supply the ethanol plant, generate surplus electricity, and create additional value streams.

Approximately 31.7% of the biogas energy is converted into useful thermal energy and directly utilised to meet the process heat demand of the ethanol plant, mainly associated with distillation and dehydration stages. At the same time, the gas turbine generates electricity while supplying heat. Of this electrical output, 2.36% of the total biogas energy is used to cover the internal electrical demand of the plant, while a significantly larger share, 17.37%, remains available for export to the electrical grid.

In addition, due to the high biogas production relative to the plant's energy requirements, a substantial fraction of the energy (29.6%) remains as surplus biogas. This excess biogas can be sold and utilised as a fuel for internal combustion engines in nearby non-electrified or weak-grid rural areas, supporting decentralised energy access.

The remaining 19.0% of the energy corresponds to conversion and system losses, including inefficiencies in energy conversion, exhaust losses not recovered as useful heat, and auxiliary system consumption. As illustrated in Fig 4. Energy flow diagram, which summarises the integrated cassava–ethanol–biogas energy flows, the overall system configuration demonstrates that the available biogas energy is not only sufficient to achieve full energy self-sufficiency for the ethanol plant, but also enables a strategic allocation of surplus resources. In particular, the scheme highlights how excess electricity can be exported to the grid, while remaining biogas can be valorised beyond the plant boundaries, reinforcing efficient resource utilisation and closing the energy loop within the cassava-based production system.
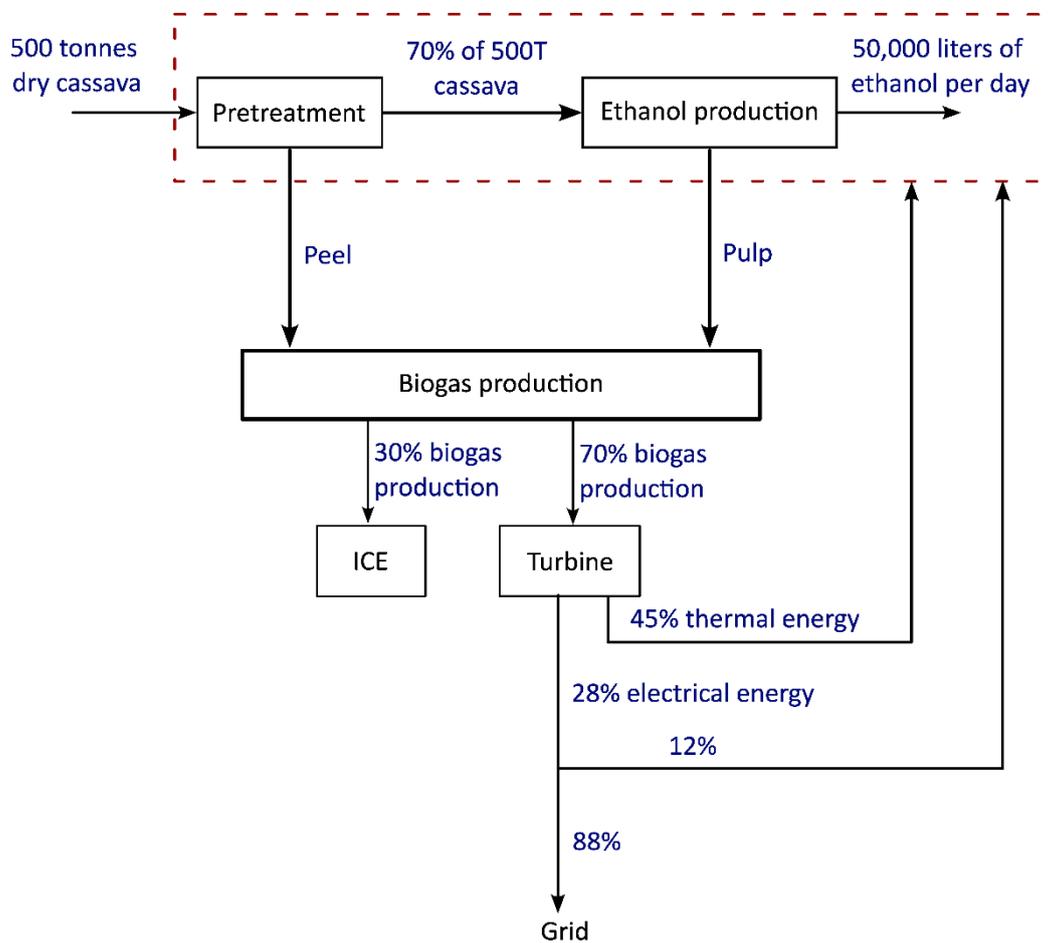

Fig 4. Energy flow diagram

8. Conclusions

Based on the results, it can be concluded that pulp produces the most biogas compared to the other substrates, with a value of 128.6 Nml/g and an RSD of 25%. Next in line are the root with 119.2 Nml/g, mix with 80.90 Nml/g, peel with 74.59 Nml/g and then the leaves with 19.73 Nml/g. Looking at the case of the Maposa Ethanol Plant, which processes 200 tonnes of cassava root and a total of 50 hectares per day, the root yields the most energy from methane production because it is a combination of peel and pulp waste with a value of 166-184 MWh. The mix is the next best option for generating energy, with a value of 153-170 MWh.

From the conversion perspective, both internal combustion engines and gas turbines are capable of efficiently transforming the biogas produced from cassava residues into useful energy, although their performance differs depending on the final energy demand. Internal combustion engines favour electrical output and operational flexibility, reaching electrical efficiencies of around 32%, while gas turbines prioritise thermal energy recovery, with thermal efficiencies of approximately 45%, which is particularly advantageous for ethanol production processes dominated by heat-intensive stages such as distillation.

The comparison between energy supply and plant demand shows that biogas derived from cassava roots can fully cover the electrical and thermal requirements of the ethanol plant. While the plant requires approximately 4.14 MWh/day of electricity and 55.6 MWh/day of thermal energy, the biogas-to-energy system is capable of producing 49–56 MWh/day of electricity and 70–79 MWh/day of thermal energy, depending on the selected conversion technology. As a result, the electrical demand is exceeded by more than an order of magnitude, and the thermal demand is fully satisfied with a clear margin.

These surpluses create additional opportunities for energy valorisation, including the export of approximately 30 MWh/day of surplus electricity to the grid and the availability of around 52 MWh/day of excess biogas energy that can be used in decentralised applications such as rural electricity generation. Overall, this project demonstrates that an integrated and technology-specific approach to energy conversion is essential to maximise the energetic value of cassava residues and to ensure the efficient and realistic deployment of biogas-based systems in the context of cassava ethanol production.

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