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Design of a Machine to Convert Municipal Solid Waste to Gas

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Abstract

This study was aimed at optimizing, automating and evaluating the viability of "B-Energy" technology for the generation of biogas from MSW waste in Sierra Leone; as part of this project, a "B-Energy" biogas plant is set up in Kenema and utilized to test various kinds of organic MSW waste. Results showed that concept 2 and 3 were the most durable and flexible design concepts to be adopted and produced for this purpose.

Keywords
Municipal solid waste, Biogas, Bio-digester, Anaerobic digester, Carbon footprint, Greenhouse gas

1. Introduction
Biogas is a renewable energy source that is produced by anaerobically digesting organic material, such as municipal solid waste (MSW). MSW is a heterogeneous mixture of waste products produced by homes, businesses, institutions, and building sites. Food waste, yard garbage, paper, cardboard, plastics, glass, metals, and other random items are

frequently included. The generation of biogas from MSW is a desirable solution for the management of waste and the generation of electricity. Biogas is a combination of gases, predominantly bio-gas (CH_4) and carbon dioxide (CO_2), that can be used as a fuel for transportation as well as for the generation of power and heat. It provides a number of environmental and financial advantages, such as lowering greenhouse gas emissions, cutting down on the quantity of waste transported to landfills, and creating a renewable energy source. The procedure entails a number of phases, including the pre-processing and sorting of the waste products, the anaerobic digestion of the organic portion to produce biogas, and the post-treatment of the digested material to create a fertilizer that is rich in nutrients (Figure 1)

Figure 2. An airial Veiw of the Kenema Plant

The diversity of the waste composition, the requirement for specific equipment and facilities, and the possibility for odors and other environmental effects all present difficulties in the production of biogas from MSW. As a result, it is crucial to thoroughly assess the viability and sustainability of producing biogas from MSW on a case-by-case basis, taking into account local laws, waste management techniques, and energy consumption (Figure 2).

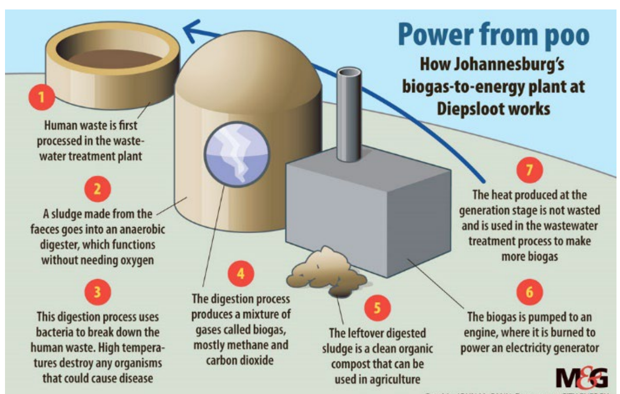

Figure 3. Step Showing how the Gas is Extra

The procedures for creating biogas from MSW are as follows:
MSW are collected and divided into organic and inorganic trash by collection and separation. Biogas generation is appropriate for organic waste, including food leftovers and yard trash.

Pre-treatment: To expand the surface area and hasten the biodegradation process, the organic waste is shred or ground. Anaerobic digestion: Pre-treated organic waste is put into a closed tank known as an anaerobic digester, where microorganisms use the absence of oxygen to break down the organic material. The digested material is collected and separated from the resulting biogas. Biogas is cleaned to get rid of contaminants such moisture, trace gases, and hydrogen sulfide (H2S). The cleaned biogas can subsequently be used as a fuel for transportation as well as for the generation of heat and power.

Designing a device that can effectively transform municipal solid waste into gas for usage in Sierra Leone is the stated problem. Like many other poor nations, Sierra Leone has problems managing trash, and turning garbage into a useful resource like gas can help solve these problems. The device needs to be made to manage the unique properties of Sierra Leone's trash, which might contain a blend of organic and inorganic components as well as a range of moisture levels and particle sizes. The machine should also be made to run economically and sustainably, utilizing resources and energy that are close at hand. The overall objective is to create a device that can effectively and efficiently turn municipal solid waste (MSW) into gas, offering a useful resource for energy production while also assisting with Sierra Leone's issues with waste management

1.1 Objectives

The major goal of this project is to optimize, automated and evaluate the viability of "B-Energy" technology for the generation of biogas from MSW waste in Sierra Leone; as part of this project, a "B-Energy" biogas plant is set up in Kenema and utilized to test various kinds of organic MSW waste. This study will concentrate on small-scale anaerobic digestion (wet fermentation) technology, helping to advance the nation's MSW treatment.

2. Literature Review

Residue management: The digested material, sometimes referred to as digestate, can be added to soil or used as fertilizer. The third-largest city in Sierra Leone, Kenema, is expanding more quickly. According to statistics from the 2004 census in Sierra Leone, the intercensal growth rate for Kenema City is 0.0264, indicating that it has a very high growth rate. With a current population of 242,364 inhabitants, the town is actually populated (projected data for population Kenema city from 2015 census). Waste management difficulties in the city have been a major source of worry. Around 96.9% of the country's cooking energy is derived from firewood and locally produced charcoal, which can result in pollution and deforestation, according to the 2015 Population and Housing Census. The Kenema city now has a reliable electricity supply, but due to the cost and shortage of electrical cooking supplies, less than 2% of the population uses it for cooking. As cities around the nation look for more affordable ways to dispose of waste, it is crucial to create technologies for the future generation and convert waste into a source of energy at current sites. Kitchen garbage (also known as food waste), glass, metal, woody waste, plastic, construction waste, and even liquid waste are all included in municipal solid waste (Lin, C.S.K., et al, 2013, Murphy and Mckeogh, 2004).

In Kenema, a sizable chunk of waste is disposed in a single sanitary landfill that was built by Welt Hunger Hilfe (WHH) in collaboration with the municipal council and is situated 5 kilometers outside of the city. Although the waste is not sorted at the home level at this location, environmental requirements are not properly upheld. More environmental effects result from illegal rubbish burning at the dump site. Given that about 40% of the waste deposit in Kenema is organic (based on data from households and the market developed as a result of this research), and that the remainder that will emerge from the digester bag after fermentation is a good organic fertilizer, there is a significant potential to produce biogas that will be used for cooking. Production of biogas is a practical technology. In this study, a digester is filled with MSW undergo a small-scale anaerobic digestion procedure. While employing MSW as a feeding material might present several difficulties, including mixing complexity, stirring time, the entrance of impurities into the digester, etc. Only 25Kg of material will be put into the digester each day for this study, and the materials will be broken down into smaller bits. Before putting the materials into the digester, a pre-composting will be done if they are significantly tougher. A tiny pilot plant created by "B-energy" will be utilized for this test because it can adapt to the country's environmental circumstances and is not widely employed in the country due to the technology (Sosnowski, et al. 2003, Khan et al. 2016, Perez et al. 2014).

3. Methods

3.1. Design Strategy

Definition of the Problem - The problem is presented in a statement that examines what the problem is, who it impacts, and why it needs to be repaired (Figure 3).

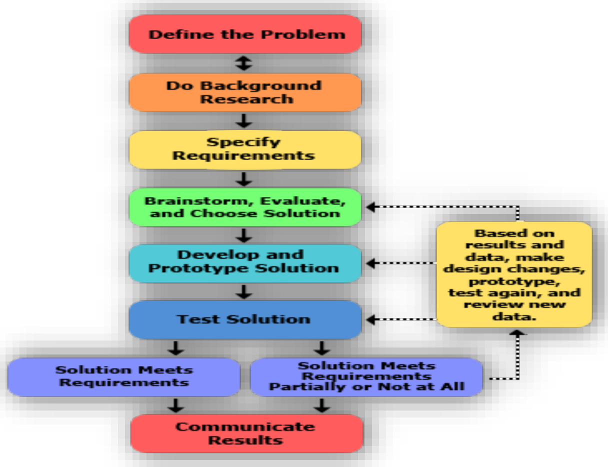

Figure 4. Flow chat for design processing

- Creating a design brief - During this step, the design's objectives, and constraints, as well as the functionality of the equipment are decided.
- Background Research a very distinctive background research is taken to remove errors when the project starts to accelerate.
- Investigating and Research - Conducting research primarily on people affected by the problem, as well as presenting designs with defects and reasons why they are not fit for a certain solution.
- Developing alternative options – Developing creative thoughts that aid in obtaining alternate answers to the problem and developing alternative solutions.
- Choosing a solution - The best solution is chosen by factors such as safety, price, and long-term viability, among others. Similar ideas are merged and be considered as one.
- Design - All design calculations are performed to identify appropriate design dimensions and attributes.
- Modeling and prototyping — A computer-aided design drawing is created to assist in communicating the concept.
- Testing and assessment solutions- Performance data from the design is collected, analyzed, and compared to the criteria.
- Communicate Results The testing findings are analyzed to determine the resolution, and if none of the solutions are optimal, the team will return and analyze the prospective solution based on the studied alternatives.

3.2. Adapt

To adapt the Kenema biogas plant to automation it is essential to ensure that all the parts of the automatic system are compatible with the existing infrastructure assistant by conducting a feasibility study to identify potential structural changes necessary to accommodate the new technology even on the model. Once this is complete the installation and testing of the automated system can be done it is important to test the system through truly before implementing it fully to ensure that it is working correctly.

Modify

Modification is an essential aspect of the automatic process. The first step is to replace the manual feed process with an automatic system this is done by integrating a control system within the plants that can detect its level and control the feed of materials automatically. To achieve these sensors are used to monitor the plants performance and make adjustments based on the data received. The control system also adjusts the mixing of the food material and water helping it maintain the proper ratio needed for optimal gas production.

Eliminate

Elimination of other parts such as a manual agitator in another crucial step in automation a Bio plant. In many cases manual agitations is performed by people and this process can be time-consuming and ineffective. By replacing manual agitation zoo with an automatic system the plant's efficiency can be significantly increased and equality of the biogas produced can be enhanced. Morfa automated agitations can ensure that the seat material is properly mixed with which will lead to better biogas production.

3.3. Design Requirements

Design requirements are the specific criteria that a product or system must meet to meet the needs of its users or stakeholders. These requirements can be related to functionality, performance, durability, safety, ease of use, aesthetics, or any other aspect of the product or system. Design requirements help designers and engineers to ensure that the product or system meets the needs and expectations of the users and stakeholders, and that it is fit for purpose. They also help to ensure that the design process remains focused and on track, and that the final product or system is delivered on time and within budget

- Biogas Plant Blueprint.
- Suitable Land with a gradient of 1-2%.
- Soil Test Report.
- Biogas Plant Design.
- Biogas reactor.
- Sealed digester tank.
- Feedstock System.
- Mixing System.
- Gas Holder.
- Gas Pipeline.
- Gas Treatment System.
- Gas Utilization System.
- Control System.
- Monitoring System.
- Safety Measures.
- Maintenance Plan.

3.4 Constraints

Designed constraints are limitations or requirements that are intentionally imposed on the design of a product or system. These constraints are put in place to ensure that the design meets certain specifications

- **Capacity:** The plant should be designed to handle a specific range of organic feedstock input and generate biogas output based on the energy demand.
- **Flexibility:** The plant should be designed to adjust to different feedstock types and composition changes while maintaining its output efficiency.
- **Safety**: The design must ensure that biosafety measures are put in place to protect the operators and nearby population.
- **Reliability:** The design should take into account backup systems and redundancy that guarantee consistent biogas production.
- **Efficiency:** The design should be optimized to ensure efficient usage of the input feedstock and maximum conversion of bio-gas gas into usable energy.
- **Environmental regulations**: The design should be in compliance with relevant environmental regulations, including odor control and waste management guidelines

3.5 Criteria

- **Stability:** The system should be capable of adapting to changing operating conditions while maintaining a stable output.
- **Durability:** The design should guarantee a long-lifespan and robustness during operation while requiring minimum maintenance.
- **Scalability:** The plant design should provide for the possibility of future additional capacity expansion.
- **Cost-effectiveness:** The system should be relatively low cost in initial investment and maintenance, and generate a high return on investment (ROI) in the short/mid-term.
- **Carbon footprint:** The plant design must provide an environmentally friendly and sustainable solution for energy generation.
- **Efficiency:** The plant must be highly efficient in using feedstock with low energy input requirements to provide a high energy output.

- **Waste utilization:** The plant design must provide overall waste management solutions by converting waste into useful energy products.

4. Results and Discussion
4.1. Functional Analysis
Functional Analysis is stated in Table 1.

Table 1. Functional Analysis

Component	Function
1. Waste collection system	Biomass such as agriculture waste, food waste or animal waste is collected and transported to the biogas plant.
2. Feedstock preparation	The collected waste material is sorted to remove non-biodegradable materials like plastic, metals, and other harmful substances. The remaining organic waste is then blended to achieve the required carbon-to-nitrogen ratio.
3. Anaerobic digestion	In this process, the blended organic waste is mixed with water and transferred to an enclosed digester. Anaerobic bacteria consume the organic matter and produce bio-gas, which is captured in the biogas plant.
4. Biogas storage	The produced bio-gas is stored in a gas holder or tank for later use.
5. Gas treatment	Before biogas can be used, it undergoes cleaning and upgrading processes. If the quality of biogas is not good enough, contaminants like water vapor, H_2S and siloxanes are removed to make it a more pure and usable fuel.
6. Biogas utilization	The purified biogas is finally used for various energy applications, such as heating, cooking, and generating electricity or is supplied to the natural gas pipeline network.
7. Digestate Management	The end product of the biogas plant is the digestate which is a nitrogen-rich organic fertilizer. In some cases, the digestate can be used as soil supplements, whereas it can also be used as animal feed after proper treatment.

The functional analysis of a biogas plant model shows that it offers an environmentally sustainable and economic solution by turning waste into energy and organic fertilizers. It also contributes to mitigating bio-gas emissions, reducing dependence on fossil fuels, and providing many benefits for the production of environmentally safe organic fertilizers for agricultural purposes.

4.2. Design Development
4.2.1. Concept Generation
Concept 1 (Figure 4)

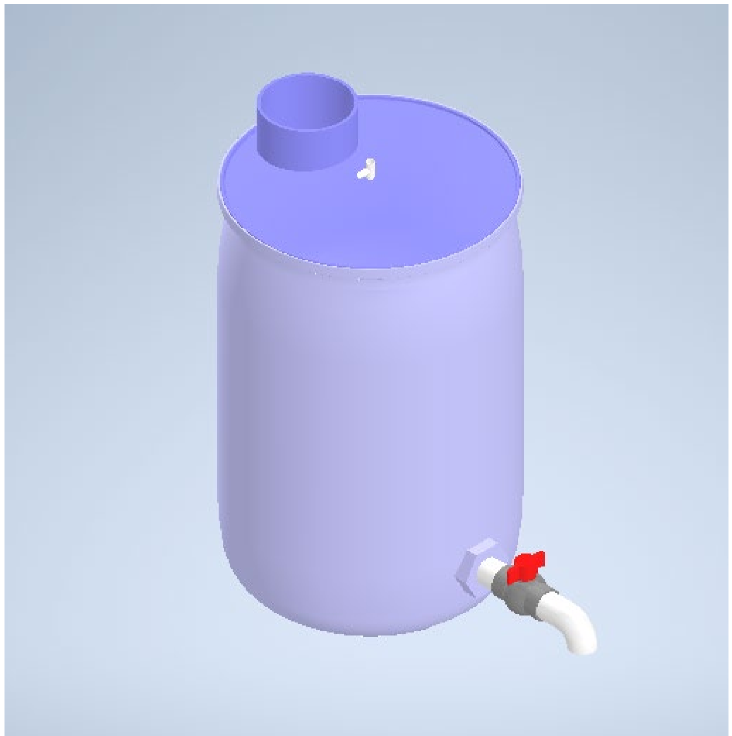

Figure 4. Concept 1 Image

4.2.2. Concept 2

Concept 2 is shown in Figure 5.

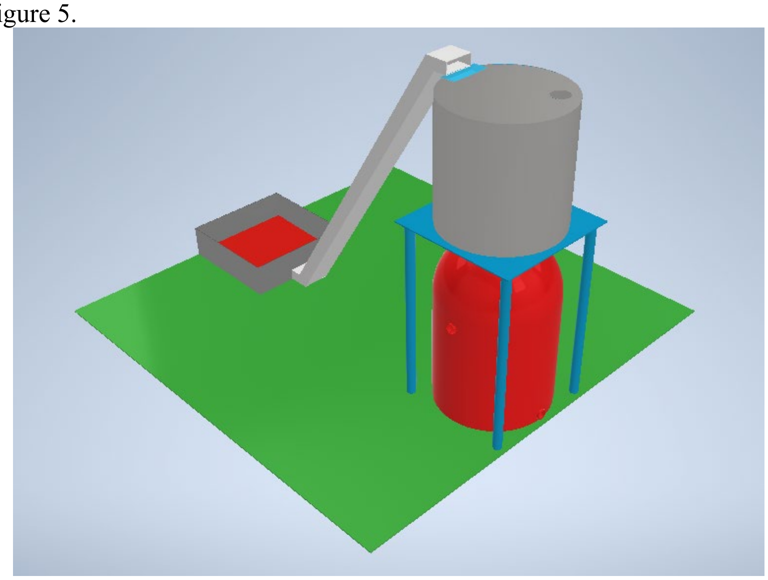

Figure 5. Concept 2 Image

4.2.3. Concept 3

Concept 3 is shown in Figure 6.

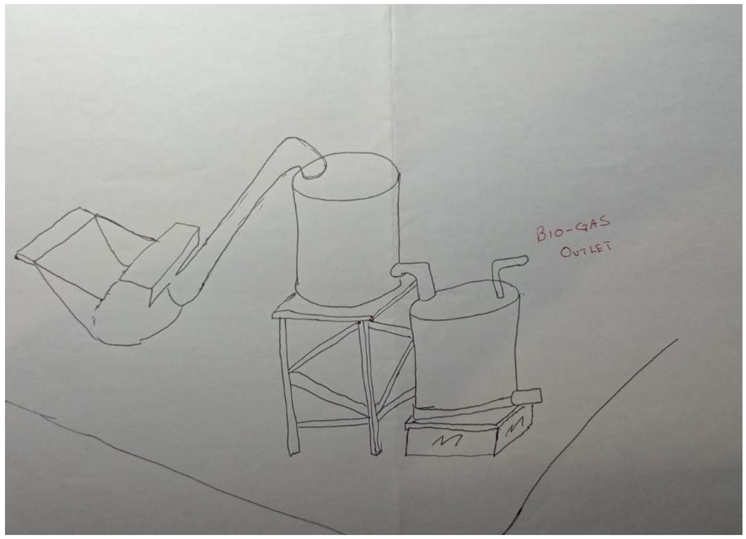

Figure 6. Concept 3 Image

4.3. Concept Evaluation

Rating Matrix is stated is in Table 2.

Table 2. Rating Matrix

DESIGN AND PROTOTYPE DEVELOPMENT OF A MACHINE TO CONVERT MUNICIPAL SOLID WASTE TO GAS							
Design Criteria	Weight	Concept 1		Concept 2		Concept 3	
		Rating	Weighting Score	Rating	Weighting Score	Rating	Weighting Score
Capacity	10%	3	0.3	4	0.4	3	0.3
Flexibility	20%	0	0	4	0.8	4	0.8
Waste utilization	25%	2	0.5	4	1	3	0.75
Safety	20%	3	0.6	3	0.6	2	0.4
Durable	10%	2	0.2	4	0.4	4	0.4
Total Score	100%		1.6		3.2		2.65
Rank		3		1		2	
Continue?		No		Yes		Yes	

Calculations

Design of digester

Dung availability=10Kg

Assume specific weight of dung is 1kg/l

Dung Volume=10l

Slurry Vol=10x2

= 20l

Retention time=40 days

Vol of Digester=20x40

=800l

=$0.8m^3$

Assume diameter : Height ratio =1:1

Vol of digester= $\pi/4\ D^2\ H_d$

$0.8 = \pi/4\ D^2(D)$

$0.8 = \pi/4\ D^3$
$D = ((4x0.8)/\ \pi)^{1/3}$
$D = 1.006m$
$D = H_d = 1m$

Design of Gas Holder
How much gas is produced per day if feeding 20l of feed in 1day?
NB in 20l of feed, 10l is cow dung

Daily Gas production=20x20
=400l
$0.4m^3$
Diameter of gas holder < Diameter of digester

Assume that $D_{gas\ holder} = D_{Digester} - 20cm$
=100cm -20cm
=80cm
Vol of gas holder = 0.2
$0.2 = \pi/4\ D^2\ H_g$
$H_g = (0.2x4)/\ \pi(0.8)^2$
=0.398m

Slurry mixing tank
Daily Slurry Vol=20l
Assume depth of 0.4m
Area=Vol/Depth
=0.02/0.4
$=0.05m^2$
Assume Square cross sectional area:L=B
$L=B=(0.05)^{1/2}$
=0.224m
=23cm

Pipe length

If y=elevation =0.5m and the distance between two tanks (x) is 1m let p be pipe length
$P^2=x^2+y^2$
$=1^2 + 0.5^2$
=1.25
P=1.12m

Elevation Angle, θ

Sin θ= y/p
sin θ= 0.5/1.12
$\theta = 26.5^0$

5. Conclusion

Upon evaluating the various design concepts for the machine aimed at converting municipal solid waste (MSW) into gas, it became evident that concepts 2 and 3 emerged as the most promising options. The decision to prioritize these concepts was based on several key factors including durability, waste utilization, and flexibility. Both concepts 2 and 3 scored notably high in terms of durability. This aspect is critical for the long-term functionality and sustainability of the machine, especially considering the harsh operating conditions and varying compositions of MSW in Sierra Leone.

A durable design ensures that the machine can withstand continuous operation and potential wear and tear, thus maximizing its lifespan and effectiveness in addressing waste management challenges.

Another crucial aspect considered in the evaluation was the efficiency of waste utilization. Concepts 2 and 3 demonstrated strong performance in this regard, indicating their ability to effectively convert MSW into gas. Waste utilization is fundamental not only for energy production but also for reducing the environmental burden of waste disposal. By efficiently utilizing waste materials, these concepts contribute to the sustainable management of MSW while also providing a valuable energy resource.

Flexibility in design is essential to accommodate the diverse range of MSW compositions and operational conditions in Sierra Leone. Concepts 2 and 3 exhibited commendable flexibility, allowing for adaptation to different feedstock types and variations in waste characteristics. This adaptability ensures that the machine remains functional and efficient across various scenarios, enhancing its practicality and usability in real-world waste management settings.

Overall, the selection of concepts 2 and 3 as the preferred design options underscores their potential to address the challenges associated with MSW management in Sierra Leone effectively. By prioritizing durability, waste utilization, and flexibility, these concepts offer promising solutions for converting MSW into gas, thereby contributing to sustainable energy production and environmental conservation efforts in the region.

The optimization, automation, and evaluation of "B-Energy" technology for biogas generation from MSW waste represent a significant step towards addressing Sierra Leone's waste management issues while simultaneously harnessing renewable energy resources. The adoption of robust and adaptable design concepts such as 2 and 3 holds great promise for the future of waste-to-energy initiatives in the country, paving the way for a more sustainable and environmentally conscious approach to waste management.

The model of the automatic Kenema biogas plant has effectively addressed the problem of waste management in the local community while also producing renewable energy. The use of an automatic system increases the efficiency and effectiveness of the plant, making it a more sustainable and cost-effective solution. The success of the project can be attributed to effective planning and implementation, community involvement, and the use of appropriate technology. The machine is reliable for improving solid waste management treatment in a country like Sierra Leone. It is safe and can be installed and operated locally. It is also economical. It will produce biogas and also organic fertilizer which is a good way to utilize the MSW within the city.

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Biographies

Reabetswe Kgomotsego Lucretia Seisho: Born and raised in Kuruman, a vibrant town in South Africa, nestled amidst the rich tapestry of South Africa's mineral and mining industry. Reabetswe Seisho emerged as an example of academic excellence and leadership from an early age. Her journey towards becoming a great figure in the field of Mechanical Engineering was marked by innate curiosity, determination, resilience, and a passion for learning. Reabetswe's educational voyage commenced at Galeletsang Science High School, where she distinguished herself as a top-performing learner. Excelling in subjects like Mathematics, Physical Sciences and English, she effortlessly balanced academic rigors with active involvement in extracurricular activities. Her natural leadership qualities shone through as she assumed a pivotal role as the Vice chairperson in the student council, for which she received an award, demonstrating her ability to inspire and lead her peers. In 2012, she completed as one of the highest achievers, claiming position 1 in her class, laying a foundation for her future endeavours. Eager to further her academic pursuits, Reabetswe embarked on a new chapter by enrolling in Mechanical Engineering at the prestigious University of Johannesburg (UJ). Her time at the university proved to be transformative as she immersed herself in the realms of knowledge and innovation. In her first year, she distinguished herself when she was invited to join the esteemed Golden Key society, a testament to her academic prowess and dedication to excellence. Driven by a thirst for practical experience and a desire to expand her horizons, Reabetswe seized opportunities to engage in vocational work, notably at Sibanye Stillwater, a prominent player in the mining industry. This experience not only enriched her understanding and insight into the real-world engineering practices but also enhancing her skill set and broadening her perspective and reinforcing her commitment to making meaningful contributions to the field. Currently on the verge of completing her Bachelor of Engineering Technology degree in Mechanical Engineering, Reabetswe continues to carve a path of distinction within her chosen field. As an active member of UJ SaiMeChe (The Society of Mechanical Engineers, Technologies and Technicians), she plays a role in the representation of the discipline of mechanical engineering at the university to new and senior students in her field. The student chapter aims to improve students' academics and experience in university, this is done by the organization of field trips to various companies and inviting prestigious industry personnel to share information about the real-world applications of Mechanical Engineering. As she nears the completion of her degree, Reabetswe aims to make a significant impact in the field of mechanical engineering. With a solid foundation built on academic excellence, practical experience and passion for innovation, she is equipped to tackle the diverse challenges and opportunities that await her in her field.

Prof. Daramy Vandi Von Kallon, Prof Daramy Vandi Von Kallon is a Sierra Leonean holder of a PhD in Computational mechanics obtained from the University of Cape Town (UCT) in 2013. He holds a year-long experience as a Postdoctoral researcher at UCT during 2013. At the start of 2014 Prof Kallon was formally employed by the Centre for Minerals Research (CMR) at UCT as a Scientific Officer. In May 2014 Prof Kallon transferred to the University of Johannesburg (UJ) as a full-time Lecturer, Senior Lecturer and later Associate Professor in the Department of Mechanical and Industrial Engineering Technology (DMIET). He currently teaches simulation-based modules at this Department to final year of Bachelors and Honours students and serves as Head of the Quality Assurance Committee of the Department. Prof Kallon has more than twelve (12) years' experience in research and ten (10) years of teaching at University level, with industry-based collaborations. He is widely published, has supervised from Masters to Postdoctoral and has graduated two (2) PhDs and twenty (20) Masters Candidates. Prof Kallon's primary research areas are Acoustics Technologies, Design and Development, Water and Energy Technologies and Vibration Analysis.

Ing. Kepia Boima Conteh, Kepia is Acting Head of Mechanical and production Engineering at Eastern Technical University of Sierra Leone. Kepia received his Bachelor in Mechanical Engineering (2001-2005) and awaiting Master in Philosophy in Energy Studies April 2024 from Fourah Bay College, University of Sierra Leone. His research interests include collection and conversion of Municipal solid waste to biogas. He has published and unpublished documents in the areas of garbage collection designed and fabricated metal dustbin, Topic "Metal Dustbin Fabrication (Project designed to help combat the problem of garbage collection in the Cities and Town of Sierra Leone)-a case study in Kenema'' and had worked and currently working solving social problem in community. His work focuses on Assessing the Municipal solid waste management in Kenema. The research focuses on how and where waste are produced, collected and dispose of in the municipality. Looking into the conversion of this waste to energy
Kepia Boima Conteh has 17 years of experience in Mechanical Engineering. He has contributed to numerous projects and collaborations within country and outside. He a member of Sierra Leone Institute of Engineer.

Kelleh Gbawuru Mansaray Prof Kelleh Gbawuru Mansaray is an Engineer and one of the leading pioneers in the design and development of renewable energy programmes in Sierra Leone. He holds a Bachelor of Science degree in Physics from the University of Sierra Leone, Master of Science degree in Renewable Energy Technologies from Carl von Ossietzky University in Germany, a Doctor of Philosophy degree in Biological Engineering (with specialization in Bioenergy Systems) from Dalhousie University in Canada and a one-year experience as a postdoctoral researcher in Chemical Engineering at the University of British Columbia in Canada among other qualifications. He is currently the Deputy Vice Chancellor of Fourah Bay College, University of Sierra Leone. Prior to his appointment as Deputy Vice Chancellor, Prof. Mansaray served in a number of administrative leadership positions including Officer-In-Charge of the United Nations Industrial Development Organization in Sierra Leone (2013 – 2016) and Dean of the Faculty of Engineering and Architecture at Fourah Bay College, University of Sierra Leone (2017 - 2022). Prof.

Mansaray has impeccable record in the University of Sierra Leone and has brought to the University his breadth and depth of experience both as an Academic and an application-focused researcher with several publications. He has supervised many undergraduate and postgraduate student projects which have resulted in prototypes and public installations especially in the areas of applied technology and renewable energy. Prof. Mansaray has received several recognitions and awards at national and international levels including a recognition in the coveted global 2023 AD Scientific Index for his passionate contribution to the furtherance of Academia, recipient of a University of Sierra Leone award in recognition of his contribution to research, a United Nations award in recognition of his special contribution to the South-South and Triangular Cooperation and a meritorious candidate of the Natural Sciences and Engineering Research Council of Canada. He is a member of the International Association for Solar Energy Education, a member of the Professional Engineers Registration Council of Sierra Leone and a Fellow of the Sierra Leone Institution of Engineers.