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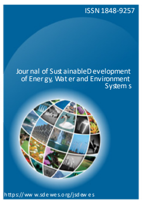

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Review Article

Review Article

Biogas Technology: A review of current practices and the potential for sustainable implementation in Eswatini

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ABSTRACT

The use of biogas in Eswatini is encouraged by favorable climate and availability of organic waste, with opportunity for renewable energy generation on site with associated health and environmental benefits. This study provides a review of the development of biogas installations with the objective of identifying the relevant factors that determine the success of biogas schemes. The study is based on local experience through a survey of about twenty biogas pilot installations in Eswatini. Data were collected using desk studies, field observations, interviews and focus group discussions. The study revealed that despite the existence of good potential, most of the biogas projects in the past experienced poor performance and were abandoned due to a multitude of factors related to policy, technical, institutional, socio-cultural, climatic and economic factors. Future implementation of biogas projects need to carefully address these relevant factors at both the planning and implementation stages and shall be accompanied by proper feasibility studies with program and project support in order to realize the full benefit and reduce failure rates.

KEYWORDS

Biogas, climate change, sustainability, anaerobic digestion, methane gas, renewable energy

INTRODUCTION

The drive towards the use of renewable energy resources is increasing with time because of the global energy crisis as a result of increasing energy demands, the high cost and lack of availability of non-renewable energy resources such as energy generated from fossil fuels, coals, etc., [1]. The consumption of fossil fuels is dramatically increasing along with improvements in the quality of life, industrialization of developing nations, and increase of the world population [2]. It has long been recognized that this excessive fossil fuel consumption not only leads to an increase in the rate of diminishing fossil fuel reserves, but it also has a

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significant adverse impact on the environment, resulting in increased health risks and the threat of global climate change [3]. In addition, the lack of alternative energy resources, the high cost of energy in the form of electricity or fossil fuels, increasing deforestation associated with the production of wood as energy resource in rural areas, and the increasing impact on climate change of the use of fossil fuels as energy resources provide further reason for considering the use of renewable energy resources. The depletion of fossil fuel reserves, the increasing generation of wastes and global warming concerns encourage increasing interest and research on the use of biogas generated from renewable resources [4].

The use of renewable energy resources such as the biogas is also part of the means of achieving sustainable development, which is the use of available resources without jeopardizing the well-being of future generations. The use of renewable energy resources is motivated partly because of the difficulty of meeting the energy demands through the use of conventional sources of energy. In addition the levels of poverty, environmental concerns, demographic and social consideration contribute to the drive towards the use of renewable energy resources such as the biogas [5]. As families gain socioeconomic status, they abandon technologies that are inefficient, less costly, and more polluting, i.e., lower on the energy ladder, such as dung, fuel wood, and charcoal. These technologies are usually more efficient and costly, but require less inputs of labor and fuel, and produce less pollution per unit of fuel [6].

Renewable energy resources include energy generated from solar energy, wind power, biomass, geo-thermal energy and energy generated from hydroelectric power. At present, renewable energy resources provide 14% of the global energy requirements in the form of biomass, hydro power energy, geothermal energy, solar power, wind power and marine energy resources [3]. Renewable energy is having a future in almost every field of the world like industrial, agricultural, medical, domestic, etc. Efficiency of solar panels is increasing and it can work even in cloudy weather. A new combined form of solar and hydro is being developed called solar/wind hybrids. This technology combines the wind turbines with solar photovoltaic (PV) panels to produce higher level of energy [7]. Renewable technologies are considered as clean sources of energy and optimal use of these resources decreases environmental impacts, produces minimum secondary waste and are sustainable based on the current and future economic and social needs [8].

Renewable energy resources that are used to satisfy the energy demands at the domestic house level have the potential to achieve a zero net emission of both air pollutants as well as Green House Gases (GHG) [3]. At the Conference of the Parties, COP 21, The United Nations (UN) member countries pledged to reduce their carbon emissions by 30% by the year 2030 and reach carbon neutrality by 2100 [9]. Waste biomasses are considered carbon–neutral fuels because the CO_2 released from their combustion is integrated into the virtuous cycle of photosynthesis of plants [10].

The use of biogas for energy generation contained in the methane gas, which is by product of the anaerobic fermentation of biomass, is a widely existing practice in areas where biomass is available and has been implemented at household, institutional and industrial levels. Naturally available waste materials such as cow manure can be easily digested through anaerobic process to yield energy [2]. Biogas energy can be used for energy generation in kitchen use for cooking foods, boiling water, as a source of electricity for rural lighting or electricity feeding the national grid and even as source a of energy driving industrial processes and cars. In rural areas, there is high dependence on fire wood as a source of energy, which naturally leads to deforestation and land degradation through erosion, in addition to the associated adverse effect on climate change. In many low- and middle-income countries of Africa and Asia, biogas produced in small digesters is used in rural areas for heating, cooking or lighting [11]. Biogas can produce energy at household levels in rural areas, which can satisfy the daily cooking needs of a family. Biogas can be generated for lighting uses. There is also potential for the use of biogas for institutional and industrial areas, Schools can use biogas through waste generated from toilets and food wastes, etc. However, the use of biogas for large-scale institutional and industrial application is limited in Africa because of technology constraints compared to the more advanced countries [4].

Biogas not only provides energy needed for household uses in rural areas. It also contributes to improvement of health, reduces poverty and contributes to the creation of local job opportunities [12]. Several health impacts of biomass burning have been identified, including chronic obstructive pulmonary disease, pneumonia, low birthweight and cataracts [13]. In general, inefficient and/or insufficient management of wastes can result in environmental as well as public health issues [14]. The use of slurry generated as byproduct from biogas use can be used in agriculture which is an economical replacement to commercial fertilizers and improves the soil health and yield of crops [15]. Bio-fertilizer (also called slurry) produced from biogas is directly applied in soil to enhance soil fertility. Bio-fertilizer (also called slurry) produced from biogas is directly applied in soil to enhance soil fertility [16]. Biogas is considered as most predictable among other renewable energy resources as it is not dependent on natural factors to the same level as for example wind, water or even solar power plants [17]. However, in the case of biogas, energy production cannot directly take from the energy source, organic matter, but depends on the institutional structures and farmers' practices involved for making energy available [18].

The use of biogas improves the housing air environment compared to the smokes produced by firewood, which can increase the risk of respiratory illness. The burden on women reduces as the need to travel long distance and carry biomass to home is reduced which is often the job of women in rural areas. The digestate from the biogas is a useful fertilizer and can be sold to users in farming practices. Biogas creates further job opportunities. Biogas reduces the use of fossil fuels, reduces the extent of deforestation, reduces the imports of energy and contributes to reducing the impacts on climate change because methane is converted to carbon dioxide, which has less global warming potential than methane. The use of biogas reduces the amount of waste that needs to be disposed as solid waste and the demand on the landfill sites to accommodate such waste.

Biogas systems have positive health advantages although from the users perspectives this may not be appreciated partly owing to lack of awareness and focus on health benefits and in general health aspects particularly in rural areas [19]. In rural areas, cow dung is thrown and is used as fertilizers on rare occasions. As a result, the environment becomes dirty, unhealthy, and smelly [20]. Organic manure is unstable in the environment, which according to the World Health Organization (WHO) has a factor of transmission of more than 100 species of various pathogens of animal and human diseases. Furthermore, it is characterized by high level of hazardous substances such as ammonia, hydrogen sulphide, mercaptan, phenol, heavy metals, salts [21].

The installation of biogas systems in both the urban and rural settings has a net environmental benefit and contributes towards reducing the impact of global warming associated with waste disposal. Cow dungs spread in the environment in rural areas have greater rate of emission of methane that has a global warming potential that is twenty times greater than that of carbon dioxide. Therefore, the conversion of methane to carbon dioxide through burning results in less overall effect on global warming. In addition, the slurry produced is used as fertilizer for agriculture that recycles the waste and thus contributing to the circular economy. The use of such slurry as fertilizer also reduces depends on inorganic fertilizers, which are more expensive and have higher carbon footprint in their production and transportation. The proper management of the biogas slurry also reduced pollution of surface and ground water sources with organic matter, nutrients and pathogens from wastes that are spread on the field.

The use of biogas reduces the extent of deforestation in search of firewood and the associated problem of land degradation as well as the net carbon footprint as result of the burning of firewood, which has a very low energy efficiency (10%).

In urban areas, dependence on non-renewable energy sources such as fuel, coal, etc., is reduced by the adoption of biogas technologies. The price of electricity continues to rise in Eswatini putting strain on the consumers who will then resort to the use of firewood as alternative energy resource thus contributing to global warming.

This study has the purpose of creating a holistic understanding of the environment under which biogas schemes succeed and of identifying the role different factors such as technical, policy, institutional, socio cultural and economic factors for sustainable use of biogas facilities in Eswatini with respect to the potential that exists in the country for energy generation from biogas. The study is based on a survey of policies and national strategies for renewable energy adoption in Eswatini including biogas and survey of assessment of performance of biogas schemes undertaken in Eswatini at various times in the past. The novelty of the study lies in the ability of the study to provide practical and useful information in the local context of biogas schemes performance in Eswatini and triangulates with the broader information available globally through similar project implementation as well as identify the local unique factors and the common factors that can play a role in the success or failure of biogas schemes. This study provides a useful information for the future planning and implementation of biogas schemes in Eswatini and beyond and will be interest to planners, designers, experts involved in biogas projects and the end users of biogas schemes.

The study as presented in this paper is organized into different sections with the Introduction part as presented in this section providing a broader perspective about biogas potential, processes and technologies and the challenges experienced with respect to the different factors that influence biogas schemes at global scale. The Materials and Methods section outlines the approach and methodology used in the study, the sampling frame for data collection, the tools that were used for collecting relevant information with respect to the performance and environment surrounding the status of biogas schemes, the types of information that were obtained, the approach for data analysis and the limitation of the study. The findings of the study is presented in the Results section with a thematic analysis of how the different factors including technical, social cultural, institutional, financial and economic factors, etc., played a role in determining the current status of biogas projects in Eswatini, contextualized with the broader observation of global biogas practice. The paper finally provides a Conclusion section highlighting the major findings of the study and recommending practical steps to be taken in order to assist with a feasible and scalable implementation of biogas schemes in Eswatini and beyond.

1.1. Biogas Process, Technologies, and Implementation Challenges

Biogas is a mixture of carbon dioxide and methane gas that is produced through anaerobic digestion of organic matter in which a solid residue called digestate remains after production of the biogas [22]. The anaerobic digestion biochemically decomposes both liquid and solid organic matter by various bacterial activities in an oxygen-free environment [11]. Biogas is considered as a renewable energy resource since waste is produced continuously and is considered part of a circular economy since the organic waste is continuously recycled as fertilizer. Anaerobic digestion is a robust, tried and tested treatment technology that can also be used for the treatment of solid waste there by reducing the emission of greenhouse gases while producing sustainable energy [23].

Historically, the initial sources of biogas production came from the treatment of sewage sludge produced from aerobic treatment of wastewater and animal manure. Later, application expanded to liquid wastewater and the organic fraction of solid waste. Industrial application of biogas digesters appeared in the middle of the Twentieth century and the interest in biogas increased in the 1970s after the global energy crisis [24]. In the eighties, industrial wastewater treated by anaerobic digestion began to grow and worldwide, the overall number of anaerobic reactors treating industrial wastewater reached over two thousand and kept on increasing since then. The main focus of anaerobic digestion optimization has been about kinetics of soluble substrates, considering acetogenesis and methanogenesis as the limiting step [25]. Scientific and industrial experiences, together with economical and policies changes of last 30 years, bring anaerobic digestion among the most environmental friendly and economically advantageous technologies for organic waste treatment and management in Europe [26]. Industries and households use biogas for heating, food industries resort to biogas as cleaner energy source that does not produce odor and particle emissions.

A broad range of biomass sources can be used as substrate for the production of biogas. These include sewage sludge, animal manure, wastes from slaughterhouses, residues from crops harvesting, algae and the organic fraction of solid waste [27]. Substrates with high moisture content (containing more than 60% water) can be directly processed [28]. Wastes that contain high concentration of lignified substances such as wood are not suitable for anaerobic digestion, as they cannot be degraded by anaerobic organisms [29]. The waste degradability can be improved by co-digestion processes, which involves the process of digestion of different types of wastes as a mixture, which results in better production of gas as well as stability of performance [30]. The suitability of a given solid waste for anaerobic digestion shall be evaluated in terms of parameters such as Carbon to Nitrogen ratio (C/N), moisture content, pH and the soluble and insoluble biodegradable content [23].

The steps in the anaerobic decomposition process consist of hydrolysis, acidogenesis, acetogenesis, and methanogens [31]. The operational parameters for monitoring the anaerobic digestion for the production of biogas include the carbon to nitrogen ratio (C/N), waste loading rate, retention time, extent of mixing of waste, temperature, pH [32], [33]. The acidification process can inhibit the action of methanogenesis for which pH control is required. This happens for example during the digestion of easily biodegradable organic matter and the production of a large amount of volatile fatty acids [34]. The acidification can be avoided through co-digestion or by addition of an alkaline substance for pH [31]. Further inhibition of the anaerobic digestion process can occur because of the presence of ammonia, sulfide, metal ions, heavy metal and other substances [27]. Inhibitory substances are often found to be the leading cause of anaerobic reactor upset and failure since they are present in substantial concentrations in wastewaters and sludge [35]. Acetylene inhibits the activity of methanogens, while chloroform inhibits metabolic process of methanogenesis [36]. High ammonia levels inhibit methane generation during anaerobic digestion [37]. High level of acetogenesis produce toxicity against the methanogenic bacteria [38]. Optimization and modelling of anaerobic digestion processes shall take into account the effect of inhibition [39].

The anaerobic decomposition process is classified according to the reaction temperature as mesophilic or thermophilic or with respect to solids concentration as high or low solids or with respect to waste feeding mode as either batch fed or continuous process [40]. The anaerobic digestion processes are also classified in different ways such as on the basis of the reactor design, operating parameters such as pH, total solids, volatile solids contents and biodegradability of substrate [41], [42]. The range below 20 °C is termed psychrophilic and is not suitable for anaerobic digestion as the reaction rate is very slow. Mesophilic systems are considered more stable and require less energy input than thermophilic digestion systems. However, the higher temperature of the thermophilic digestion systems facilitates faster reaction rates and faster gas production [43]. Dry digestion is recently employed which has the advantage of small reactor volume, low energy required for heating, better performance at higher organic loads, greater gas production and greater tolerance to presence of substances such as plastics, sand and grit while producing compost-like substrate as a byproduct that is easier to handle than the wet substrate [41]. Liquid anaerobic digestion/wet fermentation refers to substrate with total solids lower than 15% whereas solid-state digestion/dry fermentation refers to substrate with total solids higher than 15% [44]. Animal manure, sewage sludge, and food waste are generally treated by liquid anaerobic digestion, while organic fractions of municipal solid waste and lingo cellulosic biomass such as crop residues and energy crops can be processed through solid anaerobic digestion [45]. Solid state anaerobic digestion practices using lingo cellulosic biomass as feedstock have met with a few challenges, including relatively low methane yield, potential instability, and low end-product values [46].

The main types of biogas digesters in low and middle-income countries are the fixed dome, floating dome or tubular digester [43]. The biogas contains typically the most reduced substance methane between 55-60% and the most oxidized substance carbon dioxide between 35-40%. Other impurities such as such as hydrogen sulphide, nitrogen, oxygen and hydrogen are also produced [47]. The methane gas is responsible for the heating value of the gas typically producing 6 KWH per cubic meter of gas. Biogas with methane content higher than 45% is flammable [48].

The gas production rate is variable according to the source of the feed substrate, the organic matter content and composition of the substrate. Fats produce the highest methane but require longer retention time due to the low microorganism seeds. Carbohydrates and proteins show much faster methane production but with lower methane yield. The average methane yield of a solid organic waste is between 0.36 and 0.53 m^3 per kilogram of volatile solids [32], [49]. Fruits wastes produce between 0.18 and 0.732 m^3 of methane per kilogram of volatile solids while vegetable wastes produce between 0.19 and 0.4 m^3 of methane per kilogram of volatile solids [50].

Biogas is easily burnt in gas stoves. Alternatively, conversion to electricity is possible in gas generators. The electricity generation efficiency is 33% [28]. Refining of the gas is recommended when used in gas driven engines to produce electricity and is necessary for applications like fuel cells and vehicle fuels. Liquefaction of methane is not possible at higher temperature because of the low critical temperature of methane being -82^{0}C.

The byproduct solid residue of anaerobic digestion (digestate) is rich in nitrogen and, depending on the nature of the feedstock, can be utilized in agriculture as nutrient fertilizer or for soil amendment [51], [52]. The elimination of pathogens is only partial in mesophilic digestion and is more effective in the higher temperature thermophilic digestion and long retention times or with post treatment of the digestate through aerobic composting [53].

The mesophilic digester has a greater potential in tropical climates of low and middle-income countries in Africa [54]. Biogas using agricultural feedstock are common whereas urban biogas system that use waste generated within urban areas are limited [43]. Plug flow digesters provide promising potential for low and middle-income countries [55]. Methane has low energy density and require continuous use because of the expanded requirement of storage volume of such low energy volume gas. Methane biogas upgrading and bottling systems have been produced with 90-94% purity. The filtering is carried out with wet scrubbing (assisted possibly with lime addition to trap carbon dioxide and other acidic gases) whereas the bottling is carried out by compression [56]. Auto Generative High Pressure Digestion (AHPD) results in methanogenic mass build up that in turn results in great solubility in digestate of the more soluble carbon dioxide reaching equilibrium condition that produces methane gas with 90-95% purity at a pressure of 3-90 bar [57].

Biogas units can be constructed in different forms such as fixed dome, floating drum, balloon types and biogas domes constructed from earth materials, Ferro-cement, etc. The use of a particular form is dictated by cost, availability of materials, durability, availability of technical knowhow, the amount of gas produced, availability of water and biogas feed material. Fixed domes have longer life span although the cost of construction is relatively higher. Fixed domes constructed from earth materials such as soil cement can reduce the cost of construction. However, absorption of moisture and methane gas by the soil-cement blocks used for constructing the digester can occur. This will reduce the efficiency of the anaerobic decomposition of substrate through lack of moisture in addition to the loss of methane gas generated by adsorption on the walls of the digester. Floating drums are of low cost installations and locally available materials such as used oil drums can be used for the digester and floating gas storage. However, floating domes have limited gas storage capacity, can be subject to loss of gas through excess buildup of gas in the floating drums and welding of drums requires additional skills and technology which may not be available in rural areas in Africa. Balloon types of biogas installations have cheaper installation cost compared to the fixed domes. In addition, the biogas units can be designed to accommodate large storage volume of methane gas. The construction of balloon types of biogas installation is relatively easier compared to the fixed dome construction. However, the inflatable, often plastic, material used for gas storage may have limited durability due to prolonged exposure to environmental stress such as rain, wind and sun and may carry the risk of puncture if not protected properly.

1.1.1. Implementation challenges

While the benefits of biogas productions are well established and fit well into sustainable development goals, use of renewable energy resources and combating the adverse effects of climate change, in order to realize the full potential the technical, financial, social and institutional barriers need to be addressed. This in turn requires coordination and liaison amongst policymakers, technocrats, scientists, industries, regulators and the end users [58], [59]. Failures of biogas systems are commonly experienced in low and middle-income countries [59]. Causes of failures are traced back to poor technology selection, poor design and construction of digesters, inadequate operation, and lack of ownership, responsibility and maintenance by the owners, lack of project monitoring and follow up by the promotors, lack of market for biogas and the digestate and weak business models [59], [60]. Biogas systems failed to generate sufficient interest to continue operating by the users because of non-availability of technicians, insufficient gas available for food preparation/ lighting, leakage of gas through joints and connections and the extra workload generated on users of the biogas particularly women who are already burdened with other household responsibilities. Operation and maintenance failures were issues related to lack of proper training of the users and the non-availability of technicians and skilled operators or in general lack of technical backup and support [19].

Proper planning and initial feasibility study of biogas schemes are essential including the selection of anaerobic digesters that are technically, economically, socially and environmentally appropriate for the local context [61], [62]. Cost, construction, operation and maintenance issues need to be addressed in order to increase the sustainability of biogas installations. The cost of construction of fixed domes is often higher. Alternative materials can be sought to reduce the cost taking into account of course the durability and replacement costs. Digging of domes in rock areas is more costly and surface installations may need to be considered. The availability of water may have to be improved especially during drought times through water harvesting. The availability of biomass is another factor that can hinder the development of biogas. Mechanism shall be created in harvesting more biomass in order to increase the continuity of use of biogas as otherwise anaerobic process can easily be halted for lack of enough biomass feed or the rate of biogas production can become limited.

1.1.2. Technical challenges

Biogas technologies have been promoted in the past in light of their potential as viable and economic alternatives for energy generation. This is supported through initiatives at country levels and the global efforts to promote clean energy sources and mitigate climate change. However, these efforts are undermined by the lack of sustained use of biogas systems and their subsequent failure and abandonment [63]. Technical challenges to sustainable biogas operation are commonly observed. Failures of biogas systems can occur due to poor construction and installation, poor practice with respect to addition of substrate to the biogas reactor, operation and maintenance issues and lack of training and awareness by users on biogas construction [64].

When biogas is not generated at a level that users expected or when it does not satisfy the required energy demand of a family, users tend to shift focus to alternative fuel sources such as fire wood that is relatively easy to obtain [65]. This shift can result in biogas inactivity and loss of biogas function [66]. In addition users may prefer the convenience of alternative energy sources such as electricity if available at a price users can afford [63]. The inability to connect biogas installations to traditional stoves have reportedly led to discontinuation and lack of interest in bio gas adoption [67].

Poor choice of technology that is not suited to the local geographical environment in sub-Saharan Africa regions have contributed to failures of biogas systems [68]. Cracking and leaks of the biogas dome have occurred due to poor construction that did not take into account the soil conditions, ground differential settlement and correct positioning of the digester during construction [63]. Poor feeding practices lead to suboptimal operation of biogas with poor gas production or failure to produce biogas eventually leading to their abandonment. The digestate can solidify when adequate water is not added and ends up floating or settling in the biogas reactor [69]. Biogas production can also be impaired by substrate addition that results in low or high pH values which results in loss of efficiency and eventual failure [70]. Users' lack of awareness and training are also a contributing factor in this regard [63]. Attempts have been made to develop sensor technologies for remote monitoring [71]. However, this approach is not possible to duplicate under all user environments.

Poor operation and maintenance may also be a cause biogas failure such as lack of continuous addition of feedstock which can be difficult if cow dung has to be collected from free cattle grazing areas [72][68]. Feedstock may be in short supply when users do not own cattle or the cattle die due to draught [63]. Failure to use the proper mix of substrate and water can also lead to too dry or too wet conditions often caused by lack of knowledge and training of users of the biogas [66], [68].

Climatic factors can also impair biogas production with drought conditions resulting in lack of water needed for biogas reaction particularly in areas that experience regularly prolonged dry seasons [66]. Anaerobic digestion process on which biogas systems depend for gas production can become slow or even stop during winter times when the atmospheric temperature is low [73]. Biogas systems can also fail due to failure of the mechanical parts, their poor operation or the difficulty of repairing or replacing the parts due to cost and technical reasons especially in rural areas [63]. Complex and too sophisticated biogas systems can fail due to lack of availability of spare parts [74].

In the African content, the lack of skilled human resources with adequate training to repair biogas systems particularly under the rural settlement environment can be the cause of failure of biogas schemes [75]. Biogas systems may require commitment from the users on daily basis in terms of collecting feed stock and water, their transportation and addition to the biogas digester. Some systems in addition require daily cleaning which can be a burden to the users [66], [75]. The height over which the feedstock may have to be added can also be a challenge in some cases [63]. Users lack of interest in operating and maintaining biogas systems can lead to their failure and nonuse [76], [77] . Young members of the family in rural areas often migrate to urban centers in search of job opportunity which creates a gap in operation and maintenance of biogas systems [63].

1.1.3. Safety health and environmental aspects

Safety of biogas systems should be given proper consideration both at the design stage as the observation during the study tour indicated and at the operation stages. Biogas systems pose dangers in the form of gas explosions, toxic gas releases, risks due to malfunctioning of electrical and mechanical parts and fires. Accidents have reportedly occurred as a result causing minor injuries, fatalities and property damage [78]. Explosions can be caused by poor ventilation, equipment failure and human mistake. Safety measures such as gas detectors, explosion proof lights and pressure relief valves can be provided to prevent explosions [79]. Malfunctioning that result in electric and mechanical hazard can arise in biogas plants due to equipment failure or human error resulting in explosion, fires and toxic gas releases. Biogas plants should have effective maintenance and inspection methods, employ high quality equipment and ensure that users are properly trained and supervised to avoid malfunctions [79]. Fires can arise because of ignition of gases. Poor ventilation, equipment failure and human error can cause fires, Biogas systems should adopt safety procedures and emergency procedures to prevent fires [80].

On the negative side of health, biogas systems contain biological hazards that may be present during the operation and maintenance of the biogas components. Biological hazards, also abbreviated as biohazards, are substances or agents that can endanger human health [81]. Several microorganisms such as bacteria, viruses, fungi and parasites are found in biogas feedstock including cow dungs, food wastes and sewage sludge. If not handled properly the biological hazards can arise in the form of gastrointestinal illness, skin and respiratory infections [82], [83]. The use of animal manure in the form of solid fuels is practiced in rural areas in Africa, a practice that causes indoor air pollution with associated adverse health outcome as a result [84]. Biogas converts methane to carbon dioxide during use such as cooking and this results in health and environmental concerns [85]. However, compared to the use of wood based solid fuels, it has a net health and environmental benefits [84]. This is in addition to biogas being an attractive alternative to fossil fuel where this energy sources have to be imported with foreign currency [86]. In general, impurities present in biogas have several health and environmental consequences [88]. Bio methane used as gasoil substitute of is expected to improve urban air quality, because emission factors of methane are up to 10 times lower than those of liquid fuels, considering PM, VOCs and polycyclic aromatic hydrocarbons [89]. Hydrogen sulphide is heavier than air highly toxic and flammable gas. While upon inhalation, it reacts with the biological enzymes within the blood stream and results in inhibiting cellular respiration to cause sudden collapse, pulmonary paralysis, and death [90]. Besides having low odor threshold, hydrogen sulphide at higher concentration can cause respiratory paralysis [91]. Biogas is 10 time more toxic than natural gas in terms of dioxins and furans activity and emits three time more Nitrogen Oxides (NOXs) emissions than natural gas [87] [92].

Biogas processes release toxic gases such as hydrogen sulfide and ammonia. Exposure to these gases can result in significant health consequences such as respiratory distress, nausea and death. Biogas facilities must as a result have proper ventilation, users must wear adequate personal protection equipment and there must be emergency response plan to respond to the dangers as fast as possible [80].

1.2. Policy, Institutional, and Socio-Cultural Enablers and Barriers

Renewable energy policies adopted by countries have been seen to be successful in encouraging innovations in renewable energy technologies [93] [94]. Enabling policy instruments for renewable energy technology include tax reduction, greenhouse gas certificate trading, renewable energy quotas (with and without trading certificates), renewable energy targeting, feed-in tariffs, research and development programs, tax credits, and low-cost loans [95] [96]. Public policy incentives for cost internalization by renewable energy alternatives encourages the expansion and use of these technologies [97]. In general, financial incentives, obligatory schemes, quota and mandatory requirements enormously impact renewable energy application in a positive light [98] [99].

The success of biogas projects and the entire energy transformation process depends, on the one hand, on the harmonization of activities at the central, national level and, on the other hand, on taking into account the specific socio-economic features that characterize the location of the biogas plant [100]. The presence of policies such as policies on environmental protection, clean energy, climate change, and rural development create a localized context within which biogas development is considered. On the other hand, policy instruments, such as the price of other conventional fuels and feed-in-tariffs affect the competitiveness of biogas plants. The absence of policy mechanism for the removal financial barriers for example through co-financing by the beneficiaries can retard the pace of implementation of biogas schemes [93].

Effective Implementation of biogas technologies should be backed up by clear policy and strategy. In Vietnam, a national strategy was developed by the Institute of Strategy, Policy on Natural Resources and Environment (ISPONRE). ISPONRE is an institution under the Vietnamese Ministry of Natural Resources and Environment that deals with policy and planning [101]. The strategy was to build additional 140,000 biogas plants in 2010 in addition to the existing 100,000 so far built in 2009. The strategy also includes promoting biogas research and development, expand the scale and biogas number, and coordinate various activities with the different actors involved. Relevant economic instruments were applied such as environmental fee on pollution and low interest rate on loans that deal with biogas and its technology can encourage farmers to utilize biogas. In addition, farmers that use technology to treat the domestic animal waste (including biogas systems) with a scheme that reduces their taxes. Marketing strategy was developed that consisted of activities such as: identifying the scale of biogas plants (individual digesters, small, medium, etch.); supplying and household's access to the input (dung); investigate rural income in the various rural areas of Vietnam; identifying potential of private sector to invest; establishing a qualified biogas construction/maintenance team and establish a market for purchasing and selling biogas. The Vietnamese government also allocated national fund dedicated to biogas scheme. State investment focused on maintenance of biogas plants and training human capital on new technologies. A small portion was used to assist livestock farmers in the poorer area. Local governments offered financial support management of biogas plants and promotion of biogas in order to increase users. As part of implementation strategy, a steering committee was set up that consisted of representatives from the Ministry of Natural Resource and Environment, Ministry of Agriculture and Rural Development, the Ministry of Trade and Industry, the Ministry of Science and Technology and the Ministry of Public Health. The steering committee were tasked with creating a summary of the current institutions that can participate in the strategy as well as the framework for new institutions needed to aid in the national biogas program.

In Bhutan, a biogas development started with initial pilot project of building over 6000 biogas plants. The pilot project also has a capacity building strategy of training technicians, and creation of awareness and education amongst rural households on the benefits and technical aspects of the biogas as of December 2019 [102]. A strategy was also developed that consisted of: developing, strengthening and facilitating access to suitable biogas plants; upscaling the number of various sizes of biogas plants as per the potential in the country; increasing the functionality of the biogas plants through proper operation and maintenance; providing technical assistance as well as to build the capacity through training and advocacy; making biogas plants sustainable by adopting strategic measures in place; assessing and exploring the potentials for commercial biogas to combat mounting waste issues, and maximizing the benefits of biogas plants in terms of products as well as usage. A project management organogram was created with clear definition of roles and responsibilities of stakeholders. The Department of Livestock was identified as further implementing agency. Financial institutions were drawn in as having a major role in biogas plants since there is need of credit and subsidy facility in order to upscale the biogas promotion and production due to availability of other sources of energy as well as high installation cost. Private service providers such as contractors, technicians, suppliers and companies were identified with the objective of fulfilling roles such as: Supply of materials and spare parts to the project or to the users; Involvement in construction, operation and maintenance of biogas plants; Providing after sales and technical services to the biogas plants; Owning, operating and managing the biogas plants in some cases. Project application process was framed and project implementation mechanism was created that consist of: defining the roles and responsibilities of operation of biogas project office or center; Project Committee meetings and consultations; Preparation of technical and management tools; Training and capacity building; Construction and quality monitoring; Operation and maintenance; Monitoring and evaluation; financing and progress reporting.

1.2.1. Institutional/organizational challenges

The term institution is a broadly defined term whose interpretation can become context specific. It is a term that has been in use in the past for a long time [103], [104]. There is no consensus among scholars at to the definition of institution [105], [106]. Institutions has broader reach beyond the term organization in terms of establishing structure for overseeing social rules that dictate peoples interaction within and outside organizations [107] [108] . Hodgson [104] stated that an organization is a special type of institution which is characterized by a) its own established criteria to delineate its boundaries or sphere of influence, and differentiate its members from non-members, b) principles of authority that specify accountability, and c) lines of command with defined responsibilities [103]. Providing comprehensive institutional support for investment for biogas enterprises requires equipping local institutions, including local authorities, with appropriate instruments to shape and monitor the agricultural biogas market at the local level [100].

Most biogas productions in Africa are government driven and at times linked with NGOs and donor organizations with limited private sector involvement. Government interventions are a key factor in determining the success of biogas development. Biogas schemes cannot properly prosper where a proper institutional arrangement is lacking. Government provides policy instruments, provides regulation, training, support and even subsidy where this is needed. Biogas projects can be taken by government as environmental friendly alternatives and as part of the climate mitigation action plan where policy instruments such as tax exemption. Government investment programme, etc., can be applied [109]. In rural areas in Africa, there is institutional gap in service provision as well as implementation of development programs. *Ad hoc* arrangements are often made where such institutional gaps exist which often can be the source of weak project implementation and at times failure. This situation also influences the success of biogas projects in rural areas where they are more relevant. It is, therefore, necessary to properly plan institutional arrangement for developing biogas schemes including the planning, design, construction, operation, maintenance, training, marketing and other aspects. Support services in rural areas should be made available within reasonable distances of biogas users and institutional arrangement for appropriate training and support should be established in order to sustainable manage biogas projects [103].

On the other hand, while government's role is crucial for biogas development and expansion, over dependence on government institutions create a bottleneck on institutional sustainability of biogas projects. Government institutions have rigid structures and existing departments under ministries or local offices are entrusted with implementation aspects of biogas projects especially after the completion of the initial project phase involving construction of biogas facilities. Such departments and offices are often poorly staffed, under resourced and at times over stretched with low incentive for handling additional duties. Biogas facilities with such institutional arrangements are poorly attended to. The success rates of government run projects are often low where more than half of projects fail to succeed.

When there is no institutional arrangement for follow up and monitoring biogas projects, their operation, maintenance and technical support creates a knowledge gap in terms of the different factors that may have contributed to poor performance biogas systems and their nonuse. The lack of clear institutional policy direction has contributed to failures of bio gas systems in low income countries [76]. Lack of information support from supporting organization can lead to lack of awareness among biogas users who may use the biogas as a waste disposal option without the intention of using it for energy generation [63]. With a proper institutional support and direction biogas installations can achieve high quality in terms of materials used and workmanship [76]. A properly organized market setup enables availability high quality materials and products for use in biogas installations.

1.2.2. Socio-cultural challenges

Socio cultural factors need to be studied in light of their influence on the success and adoption of biogas technologies. The users' level of education for example influences how easily biogas technologies can be understood, adopted, used and maintained. In rural areas in Africa, the level of education of adults is commonly low. According to a study in Kenya [110]over 50% of the users of biogas have primary level of education or no education at all. Other studies all indicated that low level of education of members of households influenced negatively the adoption of biogas technologies [111]. Households with low level of education have low capacity of interpreting and responding to information on new innovations [112]. On the other side, even the more educated people may have unfvaouarble view of the biogas technologies as pointed out by one research study in which level of education was negatively correlated to adoption of biogas technology because people viewed it as the technology for the less educated [113]. Users' awareness and education/training should, therefore, be viewed as a two-way street in which users of different educational background need to be educated and trained about the technologies, uses, values of biogas technologies.

The age of members of the household also influences the willingness to adopt and deal with biogas technologies. According to past studies, the probability of adopting biogas increased with increasing age. This is additionally reinforced by the fact that older people have settled down and have enough savings and are willing to invest against younger members of the household who are financially speaking not yet settled [114]. Older members of the household also have more time at their disposal to commit to operating and maintaining biogas systems. Younger members of the household often feel that biogas is a backward technology that should be left to older people. They instead prefer a more developed technology such as solar power and electricity. Young people are also put off by the process of mixing dung with water which they consider as dirty and time consuming as well as fearing that such practice might expose them to skin infections [110].

Handling waste is not always a culturally acceptable practice, which can prevent people from dealing with biogas digester slurries and working with the biogas system. In addition, some people have negative superstition regarding the idea of using waste to generate useful energy. Dealing with waste such as ashes is considered as witch practice against people and there is prejudice against dealing with such kinds of wastes. Stigmatization of waste and people dealing with waste is often prevalent within the African continent. Some users of the biogas view mixing the slurry, therefore, as unpleasant activity. Cultural resistance to the use of animal and human waste for biogas use can be a major barrier to the long term implementation of biogas technologies where such barriers have been reportedly affecting the success of biogas projected implemented in Bangladesh [115], Sri Lanka [63], Ghana [116] and other Sub-Saharan African countries [73].

Gender also plays a role in the decision on whether to adopt or not of biogas technologies by households. Most rural societies in Africa are patriarchal in which male members of households are decision makers and this role gives them an advantage to make decision about adoption of biogas. If a male member of the household is not convinced about the advantages of biogas, he will not be committed and invest on it [117], [118]. This means that even if women members of the household might be interested in adopting biogas technology, they are unable to realize their wish as they do not have decision making power in the household [110]. Where female members of the household have decision-making powers, it might be a good starting point for adoption of biogas system as it is easy to convince female members of the household who are commonly burdened with the responsibility of collecting firewood and carrying out kitchen activities such as cooking.

The installation of biogas system often reinforces the existing division of labor among traditional families where women are expected to handle all household activities. Biogas adds more labor to women who are already burdened with carrying water, doing cooking, rearing children, etc. In addition, women are expected to carry water to be used for creating wet slurry, carry the solid waste, do the mixing and feed the biogas digester as well as carry away the digestate where it is required further or stored. Time is a limited resource and the required time competes with other household activities. It is necessary to involve women at early stage of project implementation and in matters of decision making regarding the biogas schemes. Traditionally male members of the household make decision-making and this practice can exclude women with negative consequence on the success of projects.

Running biogas systems may be challenged by lack of availability of labour in an environment where rapid urbanization is taking place. Children have to attend school. Young members of the household migrate to the cities in search of employment. Hiring external labour is often costly alternative and not affordable to households. Biogas plants are labour intensive as they require collection of cow dung and water; mixing the dung with water; feeding the plant; cleaning the cow shed and transporting the slurry to the farm [117], [119].

There is also limited awareness of the benefit and risks associated with biogas systems. Some people view the gas produced from biogas systems as potentially risky (justifiably so in some cases) while there is limited awareness how this risk can be reduced by proper awareness and training. There is also a view about the possible health risk due to respiratory inhalation of a leaking methane. In rural areas, the lack of expertise and education can also limit the extent of awareness and training that can be made through training unless this aspect is properly addressed.

Increased awareness raising, education and training are essential in order to provide information on the benefit of biogas systems, break the social and cultural barriers associated with the use of waste for biogas production and encourage the adoption of biogas technology.

It is also necessary to address the negative perception of biogas systems, as it is often perceived that cooking with biogas requires longer time as compared to charcoal or liquid fuels. Biogas also cannot provide the strong heat required to prepare some meals. The residual heat of charcoal keeps the meal warm, which is not possible with biogas. The amount of biogas available per day may be limited depending on the generation capacity of the biogas digester.

1.3. Economic Feasibility and financing of biogas schemes

Biogas technology, besides being simple in technological setup based on natural anaerobic decomposition of organic matter, is also relatively cheap, economical and affordable as raw materials are available within the proximity of the users at little to no cost to the users [120]. Biogas provides economic benefit of gas as energy source and fertilizer of the residue. The financial constraint of biogas technology is commonly the cost of installation of the digester dome. Biogas projects are often installed with subsides which is declining with time[121]. Traditional economic evaluation of biogas schemes installed without subsides often indicates that they are economically unviable[122] [123]. However, when the full health and environmental benefit is included in economic analysis, biogas schemes are economically viable. Economic analysis of the viability of biogas schemes should therefore be based on accurate information on the costs and benefit taking the full benefit and costs including health and environmental costs.

The cost of biogas installation generally increases proportionally with the size of the digester. A 6 m^3 digester volume cost about USD 1500 in 2006 in Ethiopia[103]. Biogas costs vary between $400-600 in 2010 according to the National Biogas programme of Cambodia report of 2009 [124]. Reduction in costs can, however, be achieved through contribution of labor by the users of the biogas and the use of local construction materials.

The economic evaluation of biogas schemes is carried out through a cost benefit analysis, which is used for comparing the benefits of biogas schemes with the associated costs required to construct, operate and maintain the schemes [125] [126]. Parameters used in the economic evaluation include the Benefit-Cost Ratio (BCR), the Net Present Value (NPV) and the Pay Back Period (PBP) [127]. The financial return on biogas investment can be calculated using the rate of return on investment. Operational costs may be neglected as with proper training, they can be carried out by members of the household without involving outsiders that require payment. Alternatively, a bare minimum of 2% of the investment cost is taken as the annual operation and maintenance cost. Bedana et al. [120] used a life span of 15 years for financial analysis of small, medium and biogas schemes. The interest rate of 8% was used. Similarly Von Eije [128] and Haque [129] used up to 15 years for constructing biogas digesters in Bangladesh. Singh and Sooch [130] and Walekhwa et al [131] used 20 years biogas life span for their financial calculation in India and Uganda respectively.

Biogas technologies can result in net economic benefit compared to firewood consumption in rural areas [132]. Annual saving in fire wood consumption varying between 2700-2900 Kg per household was obtained in Ethiopia by using biogas schemes with digester volumes varying between 6-8 m^3[133]. The higher net economic benefit of biogas schemes in rural areas is because often times households in rural areas mostly use firewood for cooking with limited access and affordability of alternative energy sources such as kerosene stoves[134]. A net economic benefit to households from the replacement of kerosene stoves by biogas plants of capacities varying between 6-8 m^3 has been reported in Ethiopia [103], [132]. Similarly, a net economic benefit from substitution of commercial fertilizers such as Di Ammonium Phosphate (DAP) by biogas slurries have been reported [135]. However, such economic net befits are dependent on bio slurries being promoted among farmers as successful and better replacements to commercial fertilizers[133].

The payback period of biogas installations can vary from as little as less than a year to five years when subsides are provided in the form of labor contribution and the use of local materials for the construction of biogas schemes [132][136]. On the other hand the Net Present Value of biogas schemes is generally positive whether subsides are considered in the economic evaluations or not. A net positive value indicates that the cost invested in the bio gas installation is less than the income generated under the prevailing discount rate used for calculating the net present values of both costs and benefits. Similarly the Benefit Cost Ratio (BCR) of biogas schemes is generally greater than one indicating the benefits are greater than the costs. BCR of biogas plants is reportedly greater than one irrespective of the size of the biogas plants [137].

MATERIALS AND METHODS

This study has the objective of determining past practices and current status with respect to the use of biogas technologies and practices in Eswatini and identifying the possible technical, institutional, socio-cultural, financial and environmental factors and constraints that influence the sustainability of biogas schemes and recommend a way forward for future sustainable implementation of the biogas technologies.

2.1. The study areas and selection of sites

The areas selected for the study are mainly based on their past history of biogas installations in Eswatini. These biogas schemes that were undertaken in the past and as revealed by the initial stage of information collection indicate three main categories. The first set of biogas installations were those that were constructed in the 1990s as part of the promotional effort and financial support provided by the United Nations. Two biogas sites that are available for inspection in the *Luyengo* area were selected for the study. The second category belong to a set of biogas units that were provided in the *Siphophaneni* area in 2013 as several biogas installations units were piloted around this area as part of a pilot project. The pilot project was part of a resettlement program for communities affected by the construction of a dam. For the survey of the biogas performances and the challenges experienced, 15 sites were visited. The third category of biogas installations consist of a set of units that were installed at various sites in the country by individuals and organizations which were part of isolated biogas promotional efforts through local ministries and government departments. The sites surveyed included one biogas unit that was installed individually at piggery site located within the Mbabane area and two institutional biogas units adopted by two different organizations. One is in the *Mbuluzi* area in *Mbabane* city and the other is located within the *Manzini* region. In total about twenty biogas installations were visited and included in the survey.

2.2. Methods and tools used for the study

The study adopted a descriptive survey methodology of present and past biogas projects, their current status and how the different factors influence the construction, operation, maintenance and future expansion of biogas projects in Eswatini. The methods used for the survey involved examination of relevant project documents, observation of the biogas schemes and their operation through visits, interview and focus group discussion among users, experts and construction personnel involved in biogas schemes.

For the purpose of data collection, the study adopted a mixed method approach involving both qualitative and quantitative data whereby the actual state of functioning of biogas schemes is enumerated through a survey and the role that the different factors mentioned above play and the challenge they pose is described through a thematic qualitative description of these factors as gathered through observation, interview, focus group discussions and desk study of secondary data. The tools employed for the data collection include: 1) Desk study and literature review 2) Rapid appraisal of the current status of biogas facilities through field observation and interview with the end users of the biogas facilities 3) Interview and focus group discussion with key informants who are experts and constructers of biogas facilities as well as staff working in organizations that promote the use of biogas facilities. Table 1 shows the data collection framework employed in the study indicating the sources of data, the type of data collected, tools used for the data collection and the number of samples used in the study.

Participants in the data collection process for interview and focus group discussion were requested for informed consent for the interview and were allowed to discontinue with participation in the process if they wish so. Due to the sensitive nature of some of the information revealed by the study and for ethical reasons, confidentiality of the data was maintained against revelation of personal as well as organizational data that might be associated with such information. The interviews were conducted with the help of local key informants who also acted as translators. All interviews were transcribed before they were considered for further analysis. In order to ensure reliability of the data collection process, the inter rater-rater reliability tool of data collection was adopted involving independent and simultaneous collection of information by members of the research group and comparing the information afterwards.

Table 1. Data collection frame of the study involving different stakeholders

Sources of data/stakeholders	Type of data collected	Tools used for data collection	Number of samples for observation/ interview
Owners/users of biogas systems past and present	Evaluation of the status of operation of biogas facilities	- Observation of the biogas facilities. - Semi structured interview with the users/owners of the biogas facilities	20
Experts involved in promotion of biogas facilities	Status of biogas implementation, challenges experienced, good practices, etc.	- Interview and discussion with the experts. - Joint observation and evaluation through field visits.	2
Biogas constructers	-Experience with design construction, operation and maintenance of biogas facilities	- Interview and discussion with the biogas constructors. - Joint observation and evaluation through field visits.	2
International NGOs and training centers	-Experience on technology, training, implementation of biogas facilities	Interview and discussion with the experts and key informants from the organizations - Joint observation and evaluation through field visits.	2
		Total number of samples in survey	26

2.3. Data analysis

In order to bench mark and validate the study with respect to the different factors that influence the sustainable use of biogas and the challenges they pose, a broader literature review was carried out to identify how these factors influence the success of biogas projects in different countries and under different user environments. The analysis of information obtained from the literature review was organized around the following thematic areas: 1) The importance, value and potential of biogas as a renewable energy alternative 2) Biogas gas processes and technologies 3) challenges commonly experienced for sustainable implementation of biogas schemes addressing policy and programs, technical challenges, institutional/organizational issues, socio cultural challenges and health/environmental issues and 4) economic feasibility of biogas schemes and lessons from international practice.

The biogas potential existing in Eswatini was evaluated by a desk study of published information and data available with respect to the biogas technology implementation carried out locally. The analysis of information of the biogas potential was made by looking at policy and project documents prepared by government ministries, departments and international partners, past publications on biogas schemes in Eswatini as well as information obtained from interview and focus group discussion among key informants and experts involved in biogas development.

Evaluation of the status of biogas use in Eswatini and identification of how the challenges experienced towards sustainable implementation of biogas technologies was carried out with respect to a number of thematic areas. These thematic areas include: 1) Operational status of biogas facilities 2) Technical challenges experienced 3) Policy and programs 4) Institutional challenges 5) Socio-cultural factors 6) Health and environment tissues and 7) Economic feasibility and lessons from international practice. Table 2 presents the issues examined within each of the thematic areas mentioned above in analyzing the data collected.

In order to determine the economic and financial visibility of biogas technologies in Eswatini, a technical design of two alternative biogas technologies were carried out. One biogas technology involved a fixed institutional biogas dome that is constructed to digest waste from a school with a population of 200 students and constructed from bricks. The second design was made for the digestion of food wastes from canteens/cafeterias using oil drums that are welded together and setup with inclination to allow the waste to flow by gravity. The bill of quantities were prepared using current prices for material and labor in Eswatini. The technical drawings are provided in this paper, which was made using the AutoCAD software.

For estimating the return on the biogas investment on these two alternative designs, the prevailing rate of return was used to estimate the net present value of energy produce form the biogas annually. The results are compared with the available cost of electricity.

The study revealed information from the users perspective, identified how the gaps created during biogas project implementation with respect to the different factors in Eswatini influences success of biogas schemes and provided an in depth understanding of the interplay among these factors as they influence the success of biogas schemes.

2.4. Limitation of the study

The study suffers from the limitation of data based on limited exposure because of the time frame used for data collection that fits to the field visits and conducting of interviews and discussions with the key informants. Furthermore, the national experience with respect to biogas planning, progammes and implementation of biogas projects as well as technical experience in Eswatini is very limited. The information gathered in this study, therefore, had to rely on the few pilot biogas projects undertaken in the past such as the ones driven as biogas promotional efforts by the UN, biogas pilot projects that were implemented as part of the resettlement program related to water resources projects and few isolated individual adoption of biogas installations through promotion by local organizations. The overall number of biogas facilities constructed in Eswatini is limited (less than 30).

With respect to the quality of data collected, there might be limitation of confirmation bias from participants who may be looking for clues and agreeing with the researchers' perceived hypothesis. In order to reduce the extent of confirmation bias, the data were collected through open and semi-structured interviews in which the participants were allowed to express their opinion freely and the researchers are passive observers while the translators facilitate the open exchange of views from participants. Members of the household who were interviewed may also not reveal true information with regard to the actual causes of failures/poor performance of biogas systems for fear of being seen as negligent and lacking sense of responsibility or lacking knowledge and awareness about the use of biogas systems. There might also be reservation by the respondents against providing negative views on local authorities/agencies responsible for provision of biogas schemes and of technical support and backup services to the users. Therefore, there might be a tendency by respondents of the interview to focus on the more natural factors such as drought, non-availability of water and substrate, etc. as the main causes for poor operation and failures of biogas plants.

Table 2. Issues examined under each of the thematic areas in the data analysis

Thematic area	Issues examined
Operational status of biogas facilities	
Technical challenges	Design and construction, technology selection, adoption of feasible technology, technical sophistication, local availability of materials and parts, availability of stoves, training and awareness, operation and maintenance, availability of substrate and water, feeding practice, climatic conditions, availability of labor, efficiency of biogas process, substrate/water ratio, technical support provided, gas treatment, safety aspects.
Policy and program	Presence of enabling policy instruments, Energy master plans. Presence of strategy for implementation of policy on biogas schemes and institutional support. Policy and programs for biogas expansion across the different socio economic sectors. Biogas piloting strategy. Harmonization of biogas master plans across national, regional and local levels. Policy mechanisms for removal of financial barriers. Financial incentives. Removal of tax barriers. Marketing strategy. Presence of national fund dedicated to biogas.
Institutional challenges	Availability of biogas implementation agency at national, regional and local levels. Organizational arrangement for project monitoring, technical back and follow up. Identification of potential private sectors, contractors, technicians that can participate in biogas investment. Presence of non-governmental and international partners for biogas programmes and support. Level of community organization and ownership of biogas programmes and projects. Presence of research and development support unit/origination. Organizational arrangement for facilitating loans and financial support.
Socio-cultural factors	Users level of education, training and awareness on biogas. The age distribution among the users of biogas and its influence on biogas adoption. Perceived health risk to users from handling of substrate used in biogas. Perception of use, advantage and efficiency of biogas against presence of other energy alternatives. Cultural and social barriers against the handling and use of waste in biogas. Perception of odor and danger generated of gas generated from biogas. Reinforcement of division of labor and burden on women because of adoption biogas technologies.
Health and environment issues	Awareness among the users of the health and environmental impact of biogas. The use of personal protection equipment for health and safety among users. Presence of ventilation and gas leakage indicator. The level of health risk among users from handling of substrate and use of biogas facilities. Extent of treatment of biogas against toxic gases. Presence of health and safety emergency response plan.
Economic feasibility and lessons from international practice.	Cost of installation of biogas facilities. The net economic benefit of biogas installations. Availability of subsidies. Cost of other energy alternatives. Savings against the use of fire wood in rural areas. Availability of local market (demand) for biogas facilities. Role of local financial institutions for facilitating credits. Role of international partnership in training, promotion, research and commercialization of biogas schemes. Presence of regional markets.

RESULTS AND DISCUSSION

The result of the study is discussed below highlighting the potential for biogas application in Eswatini, the current status of energy supply against the demand, the negative environmental impacts of the use nonrenewable energy resources, the national level policy and program support available for biogas implementation and a discussion of the current status of biogas installation and the constraints that are present in terms of technical, institutional, financial, socio-cultural aspects. The results are discussed below under the following themes: 1) Biogas Potential, Technologies, and Implementation Challenges. 2) Policy, Institutional, and Socio-Cultural Enablers and Barriers and 3) Economic Feasibility and Lessons from International Practice.

3.1. Biogas Potential, Technologies, and Implementation Challenges

In Eswatini, a significant potential for application of biogas technology for energy generation exists because of the favorable climatic factors for methane gas generation through anaerobic decomposition of biomass, the availability of biomass sources and the existence positive regional experiences of biogas generation in the Southern African region. In Eswatini, there is a significant population of livestock, which has a positive contribution for the biogas potential as 71% of the land is agricultural and feedstock for digestion is readily available [138]. Municipal solid waste in low and middle income countries largely consist of biodegradable organic matter [139], [140]. Anaerobic digestion has the potential of treating such waste, reducing the volume while at the same time producing energy from methane and nutrient-rich digestate.

The use of wood as energy resource is common in Eswatini particularly in rural areas as in the wider African continent. The majority of the population in Eswatini (78%) are concentrated in rural areas [138]. According to Hachileka [141], Eswatini has managed to increase electricity access for its population from 20 percent in 2001 to over 80 percent in 2021, representing one of the biggest advances in energy access in the world. The current coverage of electricity in Eswatini has further increased to 85% [142]. However, the availability of electricity supply form the national grid is still limited in hard to reach remote rural areas in Eswatini far from the current grid system making connection to the electricity grid economically non-viable. Nearly 80% of the electricity supply is in Eswatini is imported from South Africa and Mozambique [138]. The Eswatini Electricity Company (EEC) operated four hydroelectric plants with a total power capacity of 60.4 MW meeting only about 16% of the country's energy needs. Five Independent Power Producers (IPPs) also contribute around 110 MW using hydro, biomass, and solar PV technologies. However, the majority of Eswatini's electricity is imported, mainly from South Africa's ageing coal- fired plants, leaving Eswatini vulnerable to price fluctuations and supply disruptions due to South Africa's unreliable power supply [142]. Eswatini's heavy reliance on energy imports, primarily from South Africa and Mozambique exposes the nation to price fluctuations, leading to escalating costs that can become unaffordable for low-income households. It also creates supply uncertainties and increases vulnerability to power shortages in neighboring countries [141].

Because of the skyrocketing cost of electricity which is imported largely from South Africa and because of rationing of electricity as a result of low water levels in dams during winter and the *El Nino* events in Eswatini and South Africa, more and more people in urban and peri-urban areas in Eswatini are turning to fire wood as a source of energy particularly for heating homes, heating bathing water and for kitchen use particularly during the winter season. Only 49% of households use clean cooking methods, and much of cooking in rural areas still relies on woodlands, affecting the environment. Electricity in rural areas is mainly used for lighting, not for productive needs, due principally to affordability [142].

The use of firewood leads to increasing global warming, increasing deforestation and land degradation through erosion. Reforestation programmes at national levels are being carried out through the Ministry of Energy, Water and Mines under the Department of Forestry. However, the extent of implementation of forestry programmes is limited towards replenishing the lost forests.

The use of biogas for energy generated is still low in Eswatini because of problems with lack of institutional, policy and program drives, the limited awareness of the potential of biogas, and the limited availability of technical knowhow, skill and experience as well as the high cost of constructions of biogas facilities. There are limited if any international partnership in order to assist with biogas energy implementation in Eswatini.

3.1.1. Challenges related to technical issue

From the field visits to the installed biogas facilities in Eswatini and discussion with the end users and local experts, it was made apparent that a number of technical factors contributed to operational problems of biogas facilities almost all of which were non-functioning. Analysis of the survey data reveals the technical factors that contributed to poor performance and failure of the biogas facilities can be disaggregated in to the following thematic areas: 1) Technology selection, design and construction aspects 2) Operation and maintenance3) Training, awareness and availability of technical support 4) Policy, institutional, and socio-Cultural enablers and barriers, and 5) Economic and financing aspects.

3.1.1.1. Technology selection, design and construction aspects

In the *Siphonaneni* area where the biogas installations were provided, the biogas domes were constructed from parts that were made of plastic material and one that was imported from abroad. The parts were assembled onsite using bolts and nuts and they were installed above ground or underground. All the materials and spare parts including the installed pipes, hoses, pressure gauges and stoves and ones that may be needed for repair and replacement had to be imported from abroad. No local arrangement was made to provide such materials from within Eswatini. Therefore, the project was entirely dependent on imported materials and parts from abroad. In one instance of a household for whom the biogas was installed, it was observed that the installed plastic digester showed multiple cracks and broke into pieces partly because of poor workmanship of assembling the parts, and, when the gas pressure increased, the joints failed showing cracks (Figure 1). Examination of the plastic digester showed that the digester required many bolts and nuts for assembling the parts presumably because the digester was imported as many pieces to reduce the transportation volume. The presence of too many bolts for assembling the parts can create a source of weakness in the digester that can lead to failure of the mechanical parts [63]. Cracks in digesters can appear due to a combination of poor material used for the digester, poor workmanship in assembling the digester and poor construction that does not take into account differential settlement of the ground over which the digester is constructed [63], [68]. The failed plastic dome was removed and a second biogas dome was installed underground with better workmanship. This second dome was working for some time without a problem until the household stopped providing feed material because of the non-availability of cow dung and water. The biogas units also required special stoves that have to be imported from abroad and could not be connected to tradition stoves. Biogas units that could not be connected to traditional stoves can be a source of disinterest and nonuse especially when the stoves malfunction and could not be replaced as they have to be imported [67]. Complex and sophisticated biogas digesters can experience failure because of lack or replacement of spare parts or due to poor workmanship in assembly or failure during operation [74].

The lack of standardization or guideline on the technical design, construction, operation and management of biogas facilities in Eswatini has created a gap. It is seen that the biogas designs are mostly fixed dome designs with the associated high cost of construction. The awareness about other types of designs especially among the local users is limited. Recently the Solar Training and Renewable Energy Entrepreneurship Centre (STREEC) adopted a tubular design using expandable bags with relatively lower cost. This is a commendable practice. However, the durability aspects shall be addressed through the use of durable material for the gas storage bag and the provision proper shade as bags can deteriorate if exposed to prolonged sunshine and rain. The use of standardization is not ideal as it can limit flexibility in design and construction. Instead, guideline documents are recommended that provide information on the different types of biogas designs, their construction, operation and management.

There can be a distance between the point of generation of the methane gas and the point of use or demand for such gas. In order to enable transportation of a reduced volume of the gas to where it is needed technologies for compression of the gas are essential. Recently STREEC introduced a compression facility for the biogas produced within their compound. This is a useful technical facility, which will help in satisfying the demand for biogas and in making it competitive with other compressed natural gas sources available on the market.

Figure 1. A plastic biogas dome material that was assembled onsite but has to be replaced soon because of poor workmanship and deterioration of the material due to exposure to sun

Several of the biogas facilities that were provided to individuals were often over designed with larger capacity than the amount of waste that is brought to the digester dictates. Even if food waste is considered as feed material, the technical feasibility of biogas design at household level is affected by the daily generation of organic food waste mainly from the kitchen. A typical daily generation rate is 1 kg per day for a family of five people. However, to meet daily lighting and heating needs a generation of 5 kg/day is required. Therefore, unless waste is collected form a number of households in groups or there are other sources of organic waste such as cow dungs, biogas facilities are not technically feasible for installation at individual household level. In a similar vein, in rural areas the lack of enough livestock to generate the needed waste can limit the potential of biogas production. Approximately wastes generated form eight cattle would be needed to produce cooking gas and electricity for a household.

Failures were also observed where the material from which the biogas fixed dome was constructed deteriorated. There were also additional plastic domes that were installed in the pilot project over ground and deteriorated overtime when continuously exposed to the sun.

These domes showed cracks over time and hence eventually failed to operate. This is an example of choice of poor material, poor workmanship as well as mode of installation over ground that resulted in failure because of exposure of the dome material to the sun. The use of material for the digester should be studied early at the planning stage in light of its appropriateness for the local environment [61], [62].

One member of the community in the Siphophaneni area during the study visit revealed that the plastic biogas dome exploded as result of cracks that developed over time. It is suspected that a combination of gas pressure that is built-up because of non-use of the biogas and environmental stress on the plastic material due to the radiation from the sun may have contributed to the explosion of the biogas tank.

3.1.1.2. Operation and maintenance: Substrate feeding, labour and climate conditions

Several of the biogas installations in the Siphophaneni area experienced lack of enough feed material due to several reasons. Some of the households that adopted the biogas units did not have enough cattle. As a result, they could not get enough feed material to satisfy the cooking needs of the family. Attempts at gathering feed material from the open field involves additional labor and time and does not seem to be favored or practiced by the users. The area experiences periodic long dry periods and drought that are exacerbated by the *El Nino* tele connection. The residents recounted the *El Nino* period of 2015-2016 that resulted in cattle death, lack of feed material and water. As result, a number of the biogas units failed to operate and were abandoned during this drought period. Biogas units perform poorly or fail to operate where users experienced lack of feed material and water either due to drought or because of not owning enough cattle that can produce enough feed material [63].

With the limitation in the amount of feed material available, the gas generated was seen by the household to be not adequate for meeting the cooking needs of the household. According to the information gathered, after a period of cooking the gas pressure indicates low reading and hence the gas is exhausted. Members of the household would only get the opportunity for further cooking after they poured in more slurry into the biogas domes and waiting for some time until further gas is generated through the anaerobic decomposition process. This reveals that the feed material available is not enough to meet the cooking needs of the family.

Some members of the community did not get sufficient awareness about the limitation of the biogas capacity and expect the biogas units to cater for all the energy or cooking needs of the family. When this is not possible, this situation may discourage the community from viewing the biogas units as a true viable option for providing energy. As a result there is a tendency to abandon the biogas units in favor of the more readily available options such as firewood, kerosene stoves or even electricity [63].

Even with enough feed material available, there were indications of non-use of the biogas facilities because preference was given to alternative sources of energy such as firewood and electricity since the users considered these sources as providing better cooking powers and warmth to the food being cooked [66]. Although the respondents to the survey did not directly express such preference, indirect indicators were revealed during the interview in which the users indicated that there was too much gas build up in the digester as indicated by the gas pressure meter.

A female member of the community for whom a biogas unit was installed in that area reported that on a typical day the biogas has to be fed with slurry material using two 20-liter buckets with feed material: water ratio of 1:1. This feeding is done twice a day, one in the morning and the other in the late afternoon. A typical household would have to have about 10 cattle to gather enough feed material to run the biogas units entirely on their own. Since they did not have this number of cattle, it means they need to walk around the community to gather cow dung. This practice is considered by the member of the community as laborious and hence a hindrance to adopting the biogas units. In general, where users have to collect cow dung from open grazing areas, difficulties are experienced in getting enough feed material for the biogas digester [68] , [72].

Additional sources of biogas such as the organic portion of the waste generated by household such as from food waste and the waste available from toilets should be considered in future. However, biogas systems that use human fecal matter from toilet are a culturally sensitive matter and should be vetted for their feasibility at the planning stage with extensive consultation with the community. In addition, such biogas units that use wastes from toilets should avoid direct contact with the waste as much as possible. In addition, the feed to the biogas should only connect the toilet vault/flushing cistern to prevent dilution of the slurry by wastewater from kitchen, bathroom, sinks, etc.

Operation and maintenance conditions

The biogas digesters failed mostly in cases where the appropriate volume of waste feed and water are not supplied to the digester. The anaerobic bacteria cease to function and die if feed material and water are not continuously supplied. Poor feeding practices result with inadequate water can result in the solidification of the substrate inside the digester or floating of the substrate on the surface both of which diminish the rate of gas generation [69]. Users lack awareness regarding the appropriate wetness of the substrate feed resulting and drying of the substrate inside the digester [63]. The problem with water availability particularly during the time of drought also contributed to the drying up of the waste. One example of a failed biogas unit due to lack of feed material is shown in Figure 2.

Figure 2. A plastic biogas dome installed underground but no longer functional due to lack of feed material and water

Another example of lack of proper operation of the biogas units was revealed in one instance of a biogas unit installed by an individual in which piggery waste was used as feed material. The individual who installed the biogas units entirely covered the cost of installation and had had a high interest in the biogas technology. The biogas dome has a capacity of 20000 liters and the owner of the biogas spent over 5000 US Dollar for the construction of the biogas unit. The owner found out while operating the biogas unit that the gas production was very low. His suspicion was that the piggery waste was not as rich as cow dung in producing methane. Therefore, he was considering mixing the piggery waste with a cow dung. However, observation of the feed material to the biogas revealed that the slurry fed to the biogas was too dilute. The owner was either not sufficiently trained on how to use a suitable water to organic solid feed ratio or not regularly monitoring this slurry feed. A local expert involved in monitoring biogas units advised the owner to use a proper slurry mixture so that the feed slurry is not too dilute.

In order to improve the efficiency of gas production, co mixing of the cow dung, which has lower carbon to nitrogen ratio with vegetable waste that has higher carbon to nitrogen ratio, is beneficial. Biogas system typically requires higher C/N ratio as the anaerobic bacteria has lower nitrogen nutrient requirements. If such vegetable feed systems are not available optimization of the biogas system can become a problem. Whereas the cow dungs may be readily available if livestock is kept at the center, the collection of vegetable waste requires additional effort from farm fields, which may not always be easily carried out. The biogas units were not connected to toilets and this option was not considered culturally acceptable either

Climatic conditions

According to the information collected during the survey of the installed biogas units that were installed in 2013 around Siphophaneni area, a number of the biogas units failed to operate in 2015 following the drought created by the *El Nino* tele connection. That period of drought resulted in the death of cattle that were the source of cow dung feed material on which the biogas units depended almost 100%. During the drought, the land becomes devoid of grass, the cows have less grass to feed on and as a result the amount, and quality of the dung they produce diminishes. According to the interview with one resident of the area who operated a biogas unit, the cattle fed on dry grass and sand during the drought period and they produce less dung. In addition, the resident mentioned that water supply becomes very limited during the drought period especially in the *Lubombo* region and this affected the operation of the biogas units. The winter season in Eswatini can also experience lack of water because this is the season in the Southern hemisphere in which high pressure conditions are experienced and rainfall is very limited. Lack of water because of dry climatic conditions can impair the performance of biogas units when enough water is not added to the digester [66]. The winter season in Eswatini is also the season where cold temperatures are experienced. The synergy of cold conditions and lack of water can negativey affect the effciency of generation of gas as the anaerobic bacteria actvitiy can become low or even stop at low temperature conditions [73].

Installation of biogas increases the labor requirement of a household by way of collection, and mixing of the feed material and water, as well as addition of the mixture to the biogas digester. These are in addition to other daily routine operation and maintenance activities related to the biogas system. Such requirement for additional labor often reinforces the existing traditional division of labor in households in rural areas in which female members of the household carry the extra burden of carrying out household activities. This means that the burden of labor on female members of the household increases with the adoption of biogas units.

According to the survey of the biogas installations visited, it is often the female members of the household that are burdened with the responsibility of providing the required labour for operating biogas units. Some members of the household visited expressed the daily challenge of collecting substrate and water which lead to poor performance of the biogas digester [66], [75]. One female member of the community for whom the biogas dome was installed reported during the visit that her biogas installation failed to operate because of lack of feed material, as she did not have enough cattle and had to walk around the area asking other members of the community for cow dung. This practice increased the daily burden on her, as she did not have assistance from other members of the family. In addition, some members of the community were not cooperative enough to give their cow dung as they considered installation of the biogas units as offering selective privileges to some members of the community and, in their opinion, such privilege should have been extended to them.

Users lack of interest in operating and maintaining biogas systems can be a source of poor performance and malfunctioning of the biogas units [76], [77]. From the survey of the biogas facilities that were visited, it can be inferred that there is less interest particularly among younger members of the household in contributing labor to the operation and maintenance of biogas units and much less from the young, male members of the household. Young members of the household in rural areas often migrate to urban cities in search of jobs and education [63]. There is also generally less interest among younger members of the household in dealing with the feed material which the young consider it as the job for older people and as a source of health risk which they do not want to expose themselves to. The younger, more educated members of the family also consider biogas systems as backward-looking technology meant for the less developed areas and favor a more modern technology such as electricity and solar power [113]. This attitude can contribute towards the diminished interest in participating in operation and maintenance of biogas facilities among the younger members of the household.

3.1.1.3. Training, awareness and availability of technical support

Creation of dry conditions within biogas reactors may occur as a result of lack of knowledge and training on the proper use of the mixture between feed material and water [66], [68]. Several of the users of biogas in *Siphophaneni* area reported poor gas generation even when the users did not experience lack of substrate and water. An individual user of biogas that accepted piggery wastes in *Mbabane* also reported poor biogas generation in which the user suspected that the piggery waste would not yield enough gas compared to cow dung. However, according to the examination by local expert in biogas installations, there was too much water coming from the piggery and that was fed into the digester resulting in a watery slurry that diminished the biogas generation potential.

One institutional biogas installed around *Impakha* area became non-functional partly because of lack of proper awareness about the purpose and operation of the biogas unit. The users of the biogas, which was connected to the institutions cafeteria and the residents' kitchen- when they were told to feed the biogas digester with waste- they misinterpreted it to mean that any type of waste can be directed to the biogas unit. As a result, wastes such as papers and dusts from sweeping of floors were fed into the biogas unit. The biogas unit apparently became dry and stopped producing biogas.

According to the information collected through survey of the biogas units visited, there is generally low or no technical support and backup. There is limited organization arrangement to offer operation and maintenance support to the biogas users and there is lack of skilled human resources to repair the biogas units. Such condition can contribute to increase in the rate at which biogas units fail [75].

Local technical know on biogas systems is often limited and government operated systems run by government employees with limited training and skill on design, construction, operation and maintenance of biogas facilities can suffer from greater failure rates. Often facilities built by international partners with better experience and skill have greater success rate. However, the extent of training of local stakeholders determines how successful such projects will be going into the future. Therefore, future projects shall address strong local technical training in order to ensure sustainability of biogas facilities.

Several of the biogas projects only provide a history of installation with limited available manuals on operation and management of the facilities. Training, if any, are only limited and the users are little prepared for addressing the operation and maintenance issues and preventing failures or carrying out remedies when failures arise. Biogas providers frequently fail to provide clients with adequate training and technical support, resulting in numerous systems mal- functioning or being abandoned.

3.2. Policy, Institutional, and Socio-Cultural Enablers and Barriers

Countries that adopt renewable energy benefits have achieved success in terms of achieving innovations in renewable energy technologies [93], ([94]. Eswatini has implemented several policy and programmes towards addressing environmental protection, energy generation, combating the adverse effects of climate change. According to a stakeholder consultative meeting for the preparation of the Swaziland Energy Master Plan in 2017 [143], stakeholders pointed out that biomass could provide sufficient feedstock for up to about 150 MW of baseload power from the timber and sugar industries. Natural gas and biogas also should be considered as viable options in the future energy mix. The Rural energy master plan and implementation strategy set to attain universal access to energy including Liquefied Petroleum Gas (LPG), improved cook stoves, solar home systems and biogas [143].

As part of the nationally determined contribution to the global response to climate change, Eswatini identified biomass energy as a largest source of renewable energy potential in the country [144]. The Eswatini Nationally Determined Contributions is committed to generating 50% of energy from renewable energy resources by 2030 and the COP 28 goals to shift from fossil fuels to green energy by 2048 [142]. With its NDC, Eswatini has set its first economy-wide emissions reduction target of 5 percent by 2030 compared to business as usual [141]. Under the preferred future scenario of the Energy Master Plan 2018, Eswatini aims to achieve 676MW of domestic capacity (including coal and renewable energy sources) by 2034 to meet the projected demand and provide adequate reserves. The impending expiration of Eswatini's contract with ESKOM in 2025 further amplifies the urgency to secure a reliable and affordable energy future [142]. Recently there has been increased drive towards the use of solar power resources for electricity generation and as a source of energy for abstracting ground water in rural areas.

According to the Initiative for Climate Action Transparency ICAT [144], an effective bioenergy policy in Eswatini would not only reduce greenhouse gas emissions, but also addresses multiple socio-economic challenges, such as access to electricity, pollution, impacts to the labor market, and others. Under the ICAT project, Eswatini will use data and transparency mechanisms to assess potential impacts of the policy and objectively demonstrate progress.

However, despite the presence of well-intentioned and positive policy environments, the use of biogas as energy source is still not given a significant attention and drive besides being mentioned as a potential source. The institutional arrangement for dealing with strategy, policy and planning of biogas system is lacking in Eswatini. Such institution arrangement is primarily needed in order to spearhead biogas schemes as the experience of Vietnam suggests [101]. National programmes towards addressing the biogas potential are therefore limited. Furthermore, biogas projects are not implemented through harmonization of the activities at national, regional and local levels that takes account the different socio-economic environment under which bio gas projects are implemented [100]. Because of the cross disciplinary nature of energy and the environment, biogas schemes draw the attention of several ministries, local organizations. As a result there is a tendency for unorganized and fragment approach towards development of biogas schemes among the different stakeholders. In order to increase cross collaboration, avoid duplication and conflict of jurisdiction, there is a need for the formation of National Steering Committee of biogas programmes in Eswatini consisting of the different ministries such Environment and Tourism, National Resources and Energy, Health, Trade and Commerce, Industry as well as tertiary institutions and research centers. A clearly defined organogram would be necessary with clear definition and roles as well as responsibilities with respect to biogas development among the different stakeholders [102].

Capacity building strategy for supporting biogas development in Eswatini are limited. Such a strategy would be useful for implementation training of biogas technicians, for building awareness among rural households and for providing technical assistance [102]. Enabling policy instruments for biogas systems such as tax reduction, GHG certificate trading, tax credits and low cost loans currently are not clearly established [94], [95].

National strategy for promotion of biogas is limited in Eswatini. As a result, only a limited number of biogas facilities have been installed which according to a study carried out in 2016, all of the biogas facilities installed were non-functional [145]. A recent study by the authors also revealed that several of the biogas facilities installed are non-functional because of lack of water, lack of biomass feed material, lack of interest in using the facilities and lack of technical knowhow in addressing operation and maintenance issues and absence of institutional support and follow up of biogas implementation programmes.

Implementation of biogas energy initiative in large industrial sector shows that Eswatini has strong potential in biomass and woodchip electricity generation, including from sugarcane bagasse [142]. The Royal Eswatini has part of its electricity generated form biomass. Eswatini beverage installed Up flow Anaerobic Sludge Blanker Clarifier (UASB) as a way of anaerobic treatment of the wastewater produced in the industry but also producing biogas in the process.

3.2.1. The socio-cultural barriers

Despite the presence of pilot biogas projects that showed initial success in meeting the energy demand of households, the technology is not embraced by the broader population any further. Apart from the economic and organization factors, socio-cultural barriers also play a role in determining the level to which biogas schemes are adopted by a community. In the area in which the biogas units were installed, the level of education among adult members of the household is generally low mostly limited to primary education or no formal education. Low level of education negatively impacts adoption of technologies [111] whereby members of the community with low level of education generally low capacity for interpreting and responding to new information [112]. On the other hand, the younger and more educated members of the family tend to consider biogas schemes as the technology for the less educated [113].

There are also ethical and social barriers and taboos especially in dealing with humane fecal matter and biogas generated from human faces. Younger members of communities generally are put off by the process of mixing cow dung with water [111] and in many societies, handling waste is not a culturally accepted practice [116]. Previous study in Eswatini in connection with adoption of dry sanitation technologies revealed that over 50% of residents surveyed stated that they do not approve of recycling of human fecal matter or urine as fertilizer or for energy use due to ethical and cultural reasons. Because of the associated strong odor of human fecal matter, dealing with biogas slurry that contain human fecal waste may not be an acceptable practice by the end users. It is therefore necessary to limit/avoid contact of slurry from human fecal waste. For example, the slurry from the biogas can be directly lead to a twin-pit collection septic tank that will be alternately operated allowing drying of the slurry before withdrawal.

Gender roles also affect on the decision to adopt biogas plants by households. Many rural societies have patriarchal dominance in which male members of the household decide on investment in biogas where the female members of the household are the ones that bear the brunt of household activities involving cooking [117], [118]. Women in general have less decision power even though their interest and commitment for biogas schemes may be high [110].

3.2.2. The Institutional/organizational Challenges

Despite the presence of policy and programmes addressing in broad terms renewable energy at national level, actual institutional/ organizational arrangements for promotion and implementation of biogas programs countrywide is limited. There is no clear institutional policy direction as far as biogas development is concerned. Such specific policy direction is crucial for the success of biogas projects [76]. Most of the biogas installations visited are a result of pilot setups from specific organizations as part of resettlement programs pilot projects aimed at promoting biogas from international organizations such as the United Nations with limited linkage to local implementing institutions. The involvement of private sector, contractor in biogas development is almost nonexistent except for individual masons that are trained in the construction of biogas units as part of pilot projects. Institutional arrangement for providing technical backup, follow up of biogas progammes is limited in which the few departments under ministries or parastatals that have taken part in technical support and follow-up have had limited capacity building and skills training. Organizational arrangement for promoting research and development in biogas does not exist except for efforts by international organizations that run tertiary level program and promote renewable energy in Eswatini such as STREEC. The level of organization at community level for managing biogas schemes is very limited.

There has to be a comprehensive institutional support for investment in biogas plants [103]. This support shall include equipping local instition and authorities [100]. There has to be government sponsored programmes that include biogas as a renwable energy option [109]. Such government programs can be undertaken in the context of green investment and as part of the climate mitigation action plan. Arangment for biogas support services withn the reach of remote rural areas where bio gasunits are installed is necessary [103].

There is a need for organizational setup that deals with marketing strategy for biogas development that consists identifying the appropriate scale of biogas, identifying potential private sector to invest, establishing qualified operation and maintenance team and establishing market for purchasing and selling biogas.

The role of the private sector should be properly spelled out with respect bio gas development. The private sector can be involved in the supply of materials and spare parts, involvement in construction, operation and maintenance of biogas units, providing after sales and technical services and owning, operating and managing biogas plants.

Further institutional challenges that are experiences as revealed by the study is provided below under the following themes: 1) Technical backup and support 2) Level of community ownership 3) Research and development 4) Promotional aspects

3.2.3. Technical support, community ownership, research and development

The presence of adequate institutional arrangement for providing such technical back up should be properly planned and executed as part of the biogas project schemes. The sustainability of biogas projects is negatively affected in the absence of such supporting mechanism running in the background which includes providing technical assistance [139].

Although a local parastatal was entrusted with follow-up of the operation of the biogas units, no further activity was carried out to address the greater community of the area to further upscale the biogas project. Some members of the community stopped attending training, showed diminished interest when they found out that the initial pilot stage included only few households, and there would be no further upscaling of the project in the future that would include them.

Engagement with the community is essential during the feasibility study, project planning, implementation and operation stages. According to the information collected about the biogas project implements in 2013 in the *Siphophaneni* area, members of the community were invited to a training workshop at the initial stage before the project was implemented as well as during the construction stages of the project. They were given training and orientation on the biogas installation. Some members of the community initially attended this orientation. Initially members of the community expressed interest and happiness about the biogas as a potentially viable alternative against the background of the ever-increasing electricity tariff. They participated in the digging of pits. They were present in the training given about the construction, operation and monitoring of the biogas units. However, when members of the community found out that the biogas installation cost was too high, they were discouraged from showing further interest in the biogas project viewing it as unaffordable. In addition, further engagement of the community was not made afterwards apart from this early stage induction. Provision of technical support, advice and follow up is necessary beyond the construction stages of biogas units if sustainability is to be achieved in operating and maintain these units.

The end users of the biogas particularly households- while being receptive of biogas projects which often comes with full project costs covered by government or donors - display little sense of ownership and continue to display dependency-syndrome, expecting government institutions to fix all the problems and even cover the costs. Such poor institutional linkage is often the cause of many follow-up community projects failing or being abandoned by the very users to whom the facilities are constructed. According to the interview with the local expert in Eswatini who had many years of experience of working with the community in connection with biogas installations, members of the community for whom biogas were installed often consider the biogas units as belonging to the government or NGOs that provided the units. In other words, they display much less ownership. The expert further recalled that whenever those members of the community encounter a problem with the biogas units, they would get in contact with him and say to him " your thing is not working" , thus in a way reflecting lack of ownership.

Another example of failure of proper community ownership has been revealed during a visit to one institutional biogas installation site around *Mbuluzi*. The biogas unit was provided to an institution with installation of a fixed dome of 12000 liters capacity. The dome was constructed from bricks. When it was constructed in 2018, the material cost was estimated to be around 7000 South African rand, which at the current exchange rate is valued around 350 USD. This biogas unit is now not operational and according to further information collected from the institution, there was less interest from the institution management to continue with operation of the biogas. The financial capacity was available, but the interest to continue with operating the biogas was not there. The institution has initially a number of cattle but they were later sold off. The feed material was no more available afterwards and the biogas naturally stopped operating.

Biogas process has a complexity in terms of technical, biological, social, environmental and economic aspects. Each of these components can be studied through research directed towards achieving optimum benefits in which the positive effects are maximized and the negative outcomes are minimized. Research institutes play a major in supporting the biogas sector with basic and applied research [140]. Research establishments such as the University of Eswatini have established the Renewable Energy Center. However, such centers are established without a proper university wide focus and are often 'owned' by departments. Besides, the University of Eswatini currently faces financial hardship with practically no funding available for carrying out research activities. The availability of funds at national level to carry out research is also limited.

At present institutions or centers that promote and provide training on biogas systems in Eswatini are limited. The STREEC located in *Nhlangano* has been taking recently active interest in biogas implementation. The activities by STREEC include construction of biogas schemes and providing training in design, construction and operation of biogas systems. Recently the STREEC has initiated biogas expansion scheme with a plan to construct over 100 biogas units in Eswatini. One recently inaugurated biogas unit constructed in *Mbuluzi* area is shown in Figure 3. The biogas units have reduced cost because the inflatable biogas dome is constructed from a cheaper material, namely the flexible flat high-density polyethylene material that is glued chemically to the required shape and volume. Training institutes like

STREEC can provide vital training and guidance on the expansion of biogas systems. However, additional training, research and development centers need to be established in the different regions in Eswatini in order to promote the adoption of biogas systems. The responsible government ministries and departments shall take an active role in this aspect.

It is reasonable to predict that there would be much more interest in adopting biogas units if there would have been a proper local institutional arrangement for introducing and popularizing the biogas technology in Eswatini. Organsiors of the annual Trade Fair of Eswatini heard about the biogas technology and provided local ministries with the opportunity of displaying this technology to the public during the trade fair shows. However, this opportunity has not been taken up, as local institutional arrangement with the responsibility of popularizing biogas, technologies have not been realized.

Figure 3. Inflatable fixed biogas dome recently constructed by STREEC and inaugurated by the Eswatini Mistry of Natural Resources and Energy

3.2.4. The health, safety and environmental aspects

Biogas technologies provide overall net health and environmental benefits compared to the use of fire wood and the presence of unused manure in the environment [86]. There is generally increased air pollution caused by fire wood and manure [84]. However and despite these benefits, biogas units still carry health, safety and environmental risks. Handling of the feed material constitutes a bio hazard [81]. If not properly protected, this bio hazard may manifest itself many forms such as gastro intestinal illness, skin and respiratory infections [82], [83].

According to the information acquired during the visit and discussion with the users of the biogas systems, the installation of the biogas systems were not accompanied with adequate training addressing the health and safety aspects. Users of the biogas systems do not commonly wear personal protection equipment to shield them from health and safety risks. This is partly due to poor knowledge, attitude and practice and partly because of economic reasons of not affording such personal protection equipment. In addition, some of the biogas facilities did not incorporate in their designs gas treatment provision that can dissolve potentially toxic gases that can pose health hazard through inhalation [86]. The kitchens in which the biogas stoves were provided did not have proper ventilation in some of the biogas installations that were visited. Lack of ventilation can expose users of the biogas to respiratory distress and nausea when personal protection equipment are not worn [80].

Accidents causing injury, fatalities and property damage associated with biogas facilities are common [78]. Such accidents can be minimized trough proper training and awareness raising among the users of the biogas as well as provision of health and safety features in design and construction of biogas facilities [79]. A biogas facility made of plastics that was provided in the Siphophaneni area was destroyed due to a fire accident. During the survey visit of the area, it was apparent that the biogas digester was exposed to fire hazards from the open solid waste dumping site and kitchen that were located in close proximity to the digester. Several of the biogas facilities visited did not have safety and emergency procedures in case of accidents which is crucial to minimize accidents and damage [80].

3.3. Economic Feasibility and Lessons from International Practice

Biogas installations, by their very nature, are large volume, high cost installations often not within the reach of affordability of the majority of users particularly at household level in rural areas. Methane is a lightweight gas with low associated energy value, which requires a large volume of gas to be generated and stored for household application purposes. However, the operation and maintenance cost of biogas installations is very low [120]. The challenge, therefore, lies in meeting the installation cost requirement of biogas units. A set of biogas installations that were piloted in 1990 in Eswatini and financially sponsored by the United Nations at the time had installation cost of 3000 South African Rand which at the current exchange rate is approximately equivalent to 150 US Dollars. This cost was not considered affordable by the rural households at that time. The costs for the materials and construction were provided by the UN and members of the community contributed free labor such as digging during construction. According to the interview with a local expert who was involved in the project in those times, there was a follow up effort to reduce the cost of the biogas installations by constructing the biogas domes from low cost soil cement blocks. However, the local expert reported that this alternative was not successful. The soil cement blocks ended up absorbing the biogas as well as the moisture inside the biogas dome. This situation created dry conditions in the dome and hence reducing the anaerobic digestion process. In addition, direct absorption of the methane gas by the soil-cement blocks reduced the biogas volume available for use.

The local expert also revealed that further attempts were made to reduce the cost of installation of biogas units by constructing the floating drums instead of the fixed domes. However, the floating drums did not store the biogas as desired and there was leakage of biogas from the floating drum. In addition, some of the construction aspects of the floating drum such as welding of drums was not feasible in the rural areas where there is no electricity and the welding technology and skilled labor availability were limited as well as the welding being a more expensive alternative.

The biogas schemes that were piloted in 2013 in the *Siphophaneni* area had fixed domes of 5000 liters capacity and were constructed of plastic parts that were assembled on site and the material cost at that time was estimated to be around 18000 South African Rand, which with the current exchange rate is valued around 900 US Dollars. At present, according to the estimate of a local expert involved in the installation of the biogas units at that time, such biogas installation would cost double this value, i.e., 1800 USD. These installations were excessively expensive for the households in those areas where the biogas units were installed and the costs were fully covered through external assistance. Members of the community were discouraged when they were informed of the costs of the material and this was considered as one of the major hindering factors that prevented the scaling up of the biogas technology in those areas on self-sustaining basis afterwards.

On the other side of the cost factor, users who can afford the current electricity tariff might be less inclined to switch to the biogas system that naturally demands greater operation and maintenance responsibility. An example of this is revealed by a visit to an institutional biogas unit that was provided in *Impakha* area and which was found to be no longer operating. According to the information obtained by this study, part of the reason for the non-functioning of the biogas unit was the lack of interest by the users of the biogas in the institution to operate it because alternative electricity supply is readily available and they are not directly responsible for covering the cost of electricity. In other words, the users afford the electricity that is readily available and did not see much reason to have to operate the biogas units that require collecting feed material and water.

A typical fixed dome biogas design in Eswatini designed for a school with a population of 200 students and with a digester volume of 20 m^3 with waste input of 16 kg per day and generating methane gas of 3.2 m^3 costs about 80,000 Emalangeni, which at the current exchange with US Dollar, is equivalent to 4000 US Dollars. This design was made of as part of the preparation of Hygiene and Sanitation Technical Design Manual for the Eswatini Ministry of Health. The design drawings are shown in Figure 4 and Figure 5 in Annex II.

In order to cut the costs of installations, cheaper gas storage medium such as used drums can be tried at household level. A preliminary design of plug flow drum digester in Eswatini shown in Figure 3, produces a bio gas yield of 720 liters of methane per day with a waste feed of 10 kg per day (on dry basis while the wet slurry is 20 kg/day with 10 kg added in 1:1 ratio) requires about 18000 Emalangeni for construction (the equivalent of which in US dollar is approximately 1000 USD) which is considered low cost in relation to a fixe dome biogas construction. The drum digester can be designed with floating drums or additional fixed drums for storing extra gas produced that could not be stored in the main drum digester. A drawing of such preliminary design is shown in Figure 6 in Annex II.

Similar cost estimates across the African continent shows variability owing to design variation, material costs, etc. In Rwanda a 4 m^3 digester has estimated cost of USD 1000, in Cameroon and Kenya $700, in Tanzania $650, in Burkina Faso $600, in Uganda $550 and in Senegal $560 [146]. Table 3 shows the comparison of the cost per cubic meter of biogas installations among the different countries.

Table 3. Comparison of costs of biogas among different countries

Country	Type of biogas unit	Capacity of digester (m^3)	Cost per cubic meter (USD)
Eswatini	Fixed dome	20	4000
Eswatini	Floating dome	1.5	750
Rwanda	Fixed dome	4	1000
Kenya	Fixed dome	4	700
Tanzania	Fixed dome	4	650
Uganda	Fixed dome	4	550
Burkina Faso	Fixed dome	4	600
Senegal	Fixed dome	4	560

Many farmers and rural households in Eswatini rely on meagre seasonal earnings, making it challenging to secure flexible loan programs for establishing and maintaining biogas systems. The average monthly income of households in urban areas in Eswatini is USD 250 and the rural households are expected to earn less than half that amount. With the relatively higher cost of installation of biogas systems, the financial sustainability of the whole biogas scheme including the capital, operation and maintenance system is very limited. In this situation, only households with higher income are inclined or willing to adopt the biogas systems. In this scenario of financial constraints, many biogas projects can only come as some sort of subsidized schemes to the end users who as a result may view such projects as not really belonging to them. As a result, the end users expect government or other stakeholders of the project such as NGOs to continue 'doing the needful' i.e., covering the operation and maintenance costs. The lack of financial sustainability and cross subsidization further feeds this dependency-syndrome where users expect to be continuously subsidized in matters of operating and maintaining the biogas facilities.

In order to finance biogas schemes and make them accessible to end users, the role of financial institutions is crucial. Such institutions facilitate provision credit and subsidy needed for upscaling of biogas systems [102]. In addition, the establishment of a national biogas fund by the government of the Kingdom of Eswatini will help in building the capacity for financing biogas schemes and make them affordable to end users [98] [99].

Economic evaluation was carried out for a fixed dome biogas design in Eswatini which was proposed for a school with a population of 200 students. With a digester volume of 20 m^3 and a waste input of 16 kg per day generating methane gas of 3.2 m^3, the digester costs about 80,000 Emalangeni, which at the current exchange with US Dollar, is equivalent to 4000 US Dollars. This design was made of as part of the Hygiene and Sanitation Technical Design Manual for the Eswatini Ministry of Health which was prepared by one of the authors of this study. The detail of the economic cost benefit analysis is shown in Annex II. The design drawings are also shown in Figure 4 and Figure 5 in Annex II.

For the economic analysis, the opportunity cost of capital of 12.5% was used as the discount rate,, i, according to the African development Bank Report of 2024. A 2% operation and maintenance cost was assumed [120] and further a design lifetime of the fixed dome digester of 25 years was assumed in the calculation. Typical design life span of biogas units assumed vary between 15 and 25 years [120], [131]. The local currency Emalangeni E is used for the calculation. According to the economic analysis results, the net present value of costs is 92127 (E) while the net present value of benefit from electricity consumption is 107432.38 (E).

Compared to the net present value of the sum of capital and running costs of 92197 (E), the gain from the biogas energy of 107432.38 (E) provides a net benefit. Therefore, over the long term there is a net economic benefit to using the biogas system even for a high cost installation of a fixed dome type. The benefit to Cost ratio (BCR) of the proposed biogas unit is 1.16 indicating a 16% net benefit over the investment in biogas. Generally, the BCR value of biogas units is greater than one irrespective of the size of the units [137]. Although, the benefit to Cost economic analysis of the proposed biogas unit is worked out against the cost of electricity in Eswatini, similar calculation done against firewood and kerosene stoves indicate positive net benefit for biogas [103], [132].

The only problem is the financing of the initial investment cost, which will be difficult to be covered by the average householder in Eswatini. Similar economic calculations at greater biogas capacity ranges and employing broader range of scenarios indicated that biogas projects do have a positive net present value indicating their economically competitive advantages [147].

The Equivalent Annual Cost (EAC) of the biogas installation under consideration was calculated as 37.5 USD. According to Bedana [120], with biogas classified as small (1.6–2.4 Cubic meters), medium (3.2 Cubic meters), and large (4.2 cubic meter) plants, the annual operating costs are calculated as: 165 USD, 200 USD and 323 USD respectively. Compared to these values, the calculated annual cost of 37.5 USD is quite low which is partly due to the high rate of return used in the calculation. With the full financial benefit under consideration including environmental benefits not considered in the above calculation, biogas plants are economically viable unlike previous analysis that considered biogas schemes as unaffordable [122], [123] [148]. In rural areas particularly because of the poor income of the households, biogas schemes may not be affordable without subsidy from outside [121]. Apart from cost considerations, performance of biogas plants also contributes to their adoption or otherwise [149]. A clear universal implementation bottleneck of biogas technologies is the financial constraint. Further, analysis is required of the use of untapped resources such as biogas and natural gas in the residential and transport sectors, and for power generation in order to increase the use of clean energy [143].

Banks often have high loan interest rates and this serves a discouraging factor against getting loans from banks in order to spread the coverage of the initial construction cost of biogas digesters over a longer period of time. Arrangement of soft loans or interest free loans for such environmentally-friendly projects would be an encouraging plan that increases the financial sustainability as well as extent of coverage of the biogas system.

3.3.1. Benefits of the International Partnership

In Eswatini, the International Aid Transparency Initiative (IATA) delegated a tertiary training center called STREEC aimed at equipping Eswatini youth with technical skills in renewable energy and entrepreneurship. Small commercial farms were chosen for initial sites within a 100 km radius of the training center for ease of monitoring, training, and engagement hubs for wider groups of low-income farmers to introduce the technology and understand the specific needs and value to the community. Innovation are largely focused on technology adoption and developing a viable and sustainable business model [138]. STREEC located in *Nhlangano* has been taking an increasing role as a focus of drive towards renewable energy resources such as biogas, solar power, wind, etc., and is providing training and consultancy services in that respect. With respect to biomass the project implemented through STREEC aims to roll out 100 digesters (plus an initial 15 prototypes) to low income farms in Eswatini and the bordering regions of South Africa. Eswatini is targeted due to the reasons stated, and South Africa is seen as a potential market expansion in neighboring regions with a similar context. This project period will be used to gain valuable market feedback through community engagement and the established methods of Smart Villages Research Group to understand and define the real needs of the local farms and communities and use this information for design revisions before future commercial rollout and continued operation [138].

Recently a high-level governmental delegation of the Kingdom of Eswatini also embarked on a three-day journey to Austria to explore biogas technology [150]. The delegation was also reportedly visiting two biogas power plants in Austria. These field trips were expected to allow the delegation to gain first-hand knowledge of the technology, assess its suitability for Eswatini's conditions, and identify potential challenges and solutions.

CONCLUSION

The use of biogas for satisfying the cooking and energy needs is a useful alternative for Eswatini with suitable environment of the climate and availability of waste biomass in both rural and urban settings. Despite the potential for development of biogas technology, the level of implementation of biogas is low in the country and the experience with the few pilot biogas projects as revealed by this study indicated that the schemes were mostly subject to poor performance and eventually ceased to operate and were abandoned due to a multitude of reasons.

Despite the existence of a several broad policy and strategy declarations in Eswatini that address renewable energy as sustainable solution for meeting energy demands and mitigate the impact of climate change, there is a lack of clear policy, strategy and direction for development specifically for biogas technology alternative at national level. As a result biogas schemes are implemented in fragmented manner as isolated projects without coordination among relevant stakeholders. There is lack of institutional setup for planning, coordinating and implementing biogas projects and building capacity for biogas development in the areas of training, operation and maintenance, technical support, marketing, etc.

From the survey of the experiences of implementation of biogas projects in the country, it was clear to observe the institutional gap in which government sponsored programmes are nonexistent, there is poor private sector engagement and the level of community organization is low and the organizational arrangement for development, support and coordination at different users levels is lacking.

A number of technical factors contributed to the poor performance of biogas installations which can be ascribed to poor planning and feasibility study that address climate, availability of feed material, water, labor, etc.; lack of skilled personnel to provide technical back up; poor technology selection including reliance on imported parts; poor workmanship; inadequate training and awareness creation and poor provision of technical and back up support.

The study also revealed that socio-cultural barriers hampered the biogas project success which were observed in the form of low interest in dealing with waste material, lack of commitment to provide the required labor for biogas operation, lack of interest from the youth, low level of education among users that contributed to low awareness and knowledge about biogas schemes and their advantage as well as the gender bias that exists which increased the burden on women and while women in society traditionally have low decision power on biogas investment and choice compared to male members of households. There were also health and safety issues observed in the study where biogas schemes posed biohazards, there were poor ventilation, lack of provision for treatment of toxic gases, lack of safety provision/hazard indicators and fire accidents that destroyed biogas digesters in the past.

The study also revealed that despite biogas providing a net positive economic benefit against the cost of alternative energy resources such as firewood and electricity, the relatively higher cost of installation of biogas puts a financial barrier on adoption of biogas schemes. There is need for provision of subsidy and establishment of national fund, seeking the support of financial institutions to facilitate credit, soft loans and economic policy instruments such as low tax on green energy alternatives. Future plans for implementation of biogas projects in Eswatini shall properly consider policy, program and strategy, establishment of proper institutional setup including organization at community level for implementing biogas projects and properly addressing the technical, socio-cultural and financial constraints at both the planning and implementation stage of projects.

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Annex I. List of abbreviations used in the paper

AHPD	Auto Generative High Pressure Digestion
BCR	Benefit Cost Ratio
C/N	Carbon to Nitrogen ratio
COP	Conference of Parties
DAP	Di Ammonium Phosphate
EAC	Equivalent Annual Cost
EEC	Eswatini Electricity Company
GHG	Green House Gases
IATA	International Aid Transparency Initiative
ICAT	Initiative for Climate Action Transparency
IPP	Independent Power Producers
ISPONRE	Institute of Strategy, Policy on Natural Resources and Environment
KWH	Kilo Watt Hour

LPG	Liquefied Petroleum Gas
MW	Mega Watt
NGO	Non-Governmental Organization
NGOs	Non-Governmental Organizations
NOXs	Nitrogen Oxides
NPV	Net Present Value
PBP	Pay Back Period
PM	Particulate Matter
STREEC	Solar Training and Renewable Energy Entrepreneurship Centre
UASB	Up flow Anaerobic Sludge Blanker Clarifier
UN	United Nations
USD	US Dollar
VOC	Volatile Organic Carbon
WHO	World Health Organization

Annex II. Economic cost-benefit analysis of a fixed dome biogas installation proposed in the Sanitation and Hygiene Technical Design Manual for Eswatini, Ministry of Health.

Using the opportunity cost of capital of 12.5% as the discount rate,, i, according to the African development Bank Report of 2024, the net present value P of the 2% operation and maintenance cost (A) for the fixed dome biogas digester can be calculated as follows. Assume a design lifetime of the fixed dome digester as 25 years and the local currency Emalangeni E is used for the calculation.

$$P_{O\&M} = A\frac{[(1+i)^{n}-1]}{i\;(1+i)^{25}} \quad (1)$$

$$A = 0.02 * 80000 = 1600\;(E) \quad (2)$$

$$P_{O\&M} = 1600\,\frac{[(1+0.125)^{25}-1]}{i\;(1+0.125)^{25}} = 12127\;(E) \quad (3)$$

The net present value of the sum of capital and running costs will be:

$$P_{sum} = P_{Capital} + P_{O\&M} = 80000 + 12127 = 92127\;(E) \quad (4)$$

Using the calorific value of produced biogas 20 MJ/m3 (1MJ = 0.267 KWH) and knowing that the daily production of energy from the methane gas of the 20 m^3 reactor with 3.2 m^3 daily gas generation rate will be:

$$E_{Daily} = 20 * 0.267 * 3.2 = 17.088\ KWH \tag{5}$$

The annual energy production rate will be:

$$E_{Annual} = 17.088 * 365 = 6237.12\ \ KWH \tag{6}$$

The net present value of this annual power production from biogas will be:

$$E_P\ = 6237\ \frac{[(1+0.125)^{25}-1]}{i\ (1+0.125)^{25}} = 47270.25\ (KWH) \tag{7}$$

Using the Eswatini Electricity Corporation tariff rate of E 2.33 per KWH for domestic consumption, the net present value of the biogas energy produced will be:

$$P_{EP}\ =\ 47270.25\ (KWH) * \frac{E2.33}{KWH}\ = 107432.38\ (E) \tag{8}$$

The equivalent annual cost (EAC) of the biogas installation under consideration is calculated as:

$$EAC = \frac{NPV}{A_{tr}}\quad ;\quad A_{tr}\ = \frac{1-\frac{1}{(1+i)^n}}{i} \tag{9}$$

$$A_{tr}\ = \frac{1-\frac{1}{(1+0.125)^{25}}}{0.125}\ =\ 7.579 \tag{10}$$

$$EAC = \frac{NPV}{A_{tr}} = \frac{92197}{7.579} = 675.3\ (E) = \frac{675.3}{18} = 37.5\ USD \tag{11}$$

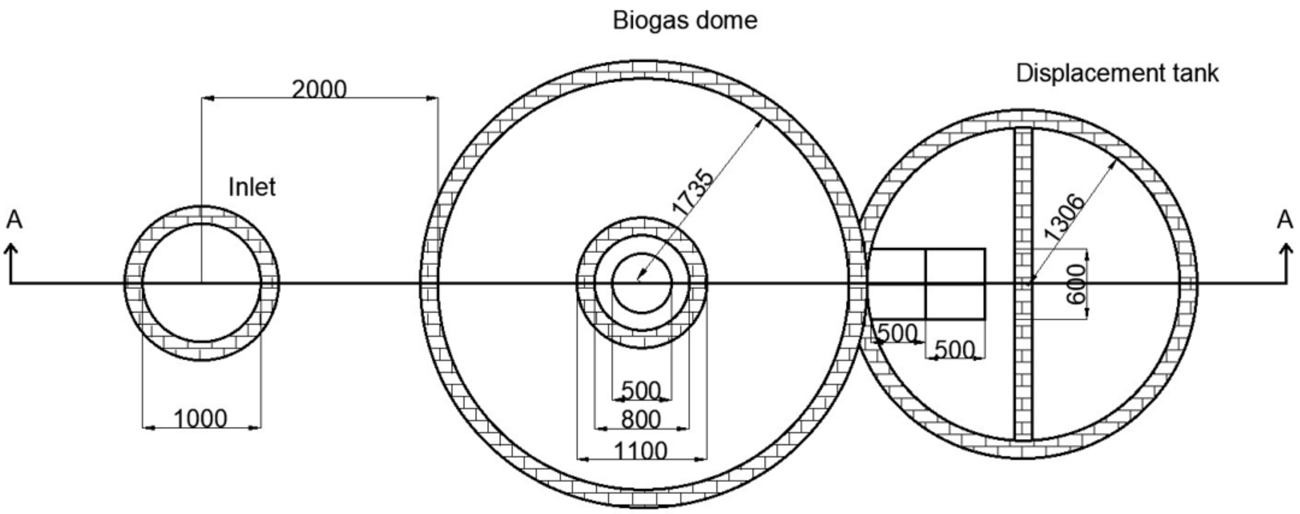

Figure 4. Fixed dome brick material boo gas design: Plan drawing

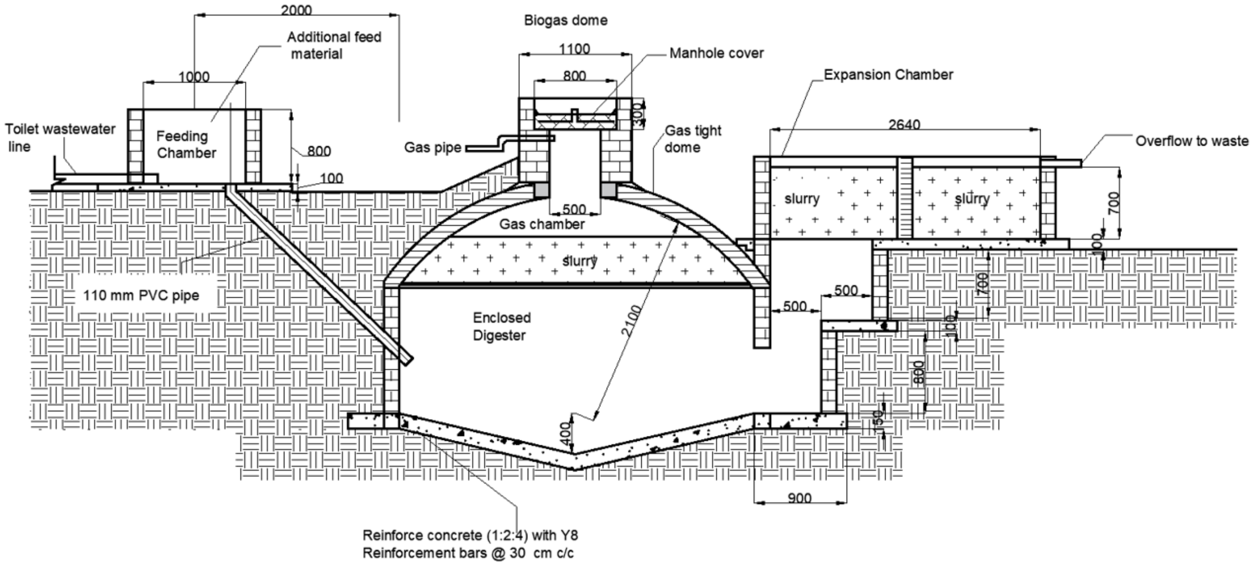

Figure 5. Fixed dome brick material boo gas design: Vertical Section A-A

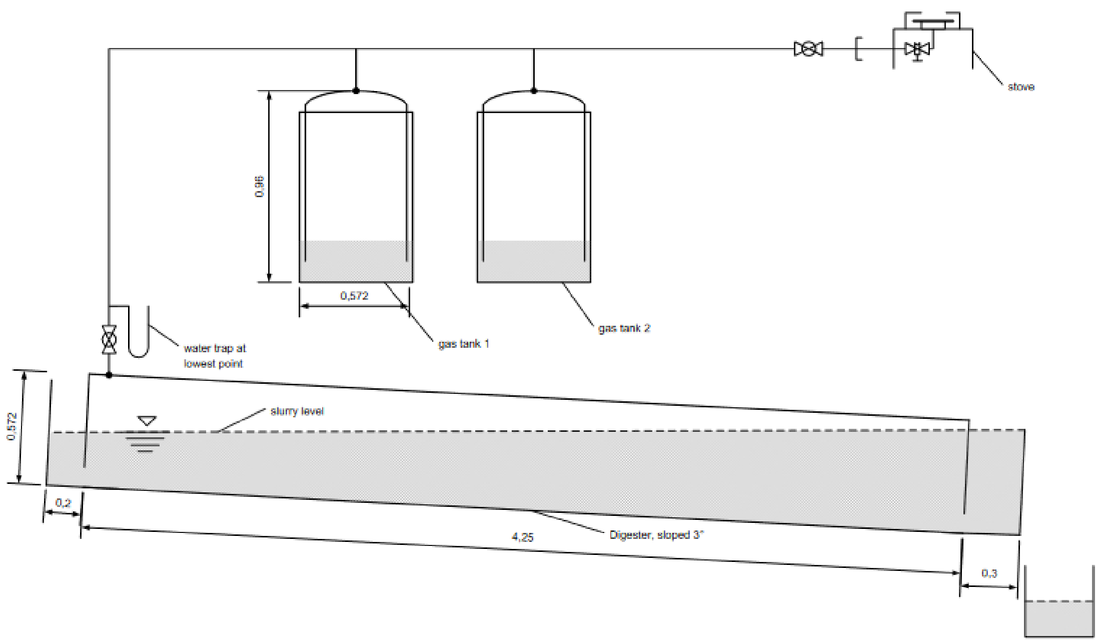

Figure 6. A plug flow drum digester design for digestion of 10 kg of organic/food waste per day