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Rural domestic biogas supply model for Zambia

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ABSTRACT

There is potential of producing biogas in rural areas of Zambia where rearing of cattle and other livestock exists. With feedstock and financial resources, people in rural areas could form groups or co-operatives and install digesters with sizes ranging from 12 to 1000 m^3. Generally the initial investment costs decrease with increase in digester size and decrease in the number of digesters to be installed. Economic analysis indicates that these digester sizes would be viable with positives Net Present Values (NPVs) at the nominal base rate of 18% up to about 37% when NPVs start to be negative. The payback period ranges from 1.3 years to about 3 years depending on size and investment costs. Biogas production results in an opportunity cost of US$0.01/ kg dry dung. Biogas would replace the use of biomass for cooking energy needs. Currently burning of biomass on inefficient stoves leads to respirable particulate matter exposure ranges from 125 to 2125 $\mu g/m^3$ which is above the World Health Organization guidelines. Implementation of biogas production in the Chitete settlement real case example would result into 3.022 $GgCO_2eq$ avoided emissions from the use of biomass for cooking using inefficient stoves, manure management and chemical fertilizer application, conserve 9.48 t of nitrogen from avoided biomass consumption for cooking, production of 336 t of organic fertilizer at a net income US$ 224,978 per year, saving of 2171 t of firewood worth US$ 57,000 and 948 t of charcoal worth US$ 95,000 per annum.

1. Introduction

Fossil fuels contribute about 80% of the world energy consumption. However, geological reserves of fossil fuels are believed to be depleting. The use of fossil fuels to meet energy needs for cooking, transportation and industries generate environmental emissions; the many benefits of renewable energies including reduced emissions have prompted renewed interest in the substitution of fossil fuels by renewable energies. Biogas which can be produced from municipal solid waste, sewerage, livestock manure, crop and forest residues is one of such renewable energies [1]. Biogas can be used as fuel to provide energy for cooking, lighting, heating and electricity generation [2]. Biogas is a biomass based renewable energy; by 2009, biomass contributed about 13% towards energy demand globally and by 2012 biomass primary energy supply had reached 55 EJ per annum [3]. In the sub-Saharan Africa, biomass accounts for about 80% of the energy supply [4] and in Zambia, biomass contributes about 83% to the total primary energy supply [5].

The use of traditional biomass using inefficient stoves has a lot of disadvantages as compared to the use of modern biomass-to-energy conversion technologies. For example, cutting of trees for charcoal or firewood reduces the forest cover which consequently degrades the soils and reduces the fauna species that depend on the flora. In short, the removal of forests brings about disturbance in the ecosystem [6,7]. Traditional woodfuel production systems have an adverse impact on the quantity and quality of soils and water, site productivity, biodiversity and the ecology [8]. The consumption of traditional biomass using inefficient stoves has very low efficiencies as compared to the best available modern technologies [9–11]. According to Fullerton et al. [12], Sambata et al. [13] and Semple et al. [14], the use of biomass in a traditional manner using inefficient stoves has resulted in respiratory diseases and to some extent even death.

Biogas dissemination and use has played a very important role in the developing world since the early 1970s. Though in some countries, especially in sub-Saharan Africa, biogas dissemination has been hampered lack of promotion of biogas energy through policy, financing, lack of skills, inflexible customs and traditions, lack of research and development and lack of incentives [15–17]. In other regions of sub-Saharan Africa, poverty and political instability are among the barriers of biogas dissemination [18].

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Biogas was first discovered by Shirlley in the mid-17th century and a century later Volta discovered the presence of methane in biogas. In the 19th century, Louis Pasteur and his student Ulysse Gayon performed anaerobic fermentation experiments. The development of microbiology as a science led to research by Buswell and others in the 1930 to discovered anaerobic bacteria and conditions necessary for biogas production [19]. The first experiment of biogas utilization in Bombay, India was conducted in 1859 [20,21] and in Exeter, England the first experiment of street lighting using biogas was carried out in 1895 [22,23]. Other the countries which pioneered research in biogas use were Germany, Italy, Denmark and China between the 19th and 20th centuries. By the end of the 20th century, India had put up almost half a million digesters in its rural areas and China had also built more than 7 million digesters along the Yellow River basin [24].

Today, biogas production is widespread across Europe, Asia and America. In Europe Germany, Switzerland, Italy, Belgium, Sweden, and Denmark operate both domestic and industrial biogas plants. In the developing world, India, China, Nepal, Tanzania, Rwanda and Uganda are some of the countries that are in biogas production and usage [25,26]. By the end of 2011, China had about 160 million people comprising of almost 42 million households mostly rural based using biogas [27]; in India 4.2 million biogas digesters were installed and it is estimated that India has sufficient resources to install between 16 and 22 million digesters in total [28–30]; Nepal has potential for 1.3 million plants and 260,000 digesters have been installed so far [31]; in Africa, Tanzania has installed about 4000 domestic digesters, while Kenya and Ethiopia have each installed hundreds. Biogas for better life has put up an ambitious biogas programme that plans to install more than 2 million digesters in Rwanda, Kenya, Uganda, Ethiopia, Cameroon, Benin and Bukina Faso [32].

In the absence of oxygen, microorganisms anaerobically produce biogas from biomass feedstock [33]. In developing countries, domestic biogas digesters are common and the main feedstock types are livestock manure, human waste, municipal waste and wastewater [34,35]. Crop and forest residues could also be used to produce biogas though they may require pre-treatment [36]. Biogas normally contains 50–70% methane, 35–50% carbon dioxide [37,38] and trace gases like hydrogen sulphide, depending on the feedstock type. For 60% methane content, biogas has a calorific value of about 21–24 MJ/m^3 or 6kWh/m^3 [39,40]. Globally, biomass contributes 75–90% of the total energy consumption [41] and 40% of the global population use biomass in a traditional manner to meet their energy needs [42]. In some of the Sub-Saharan Africa countries, biomass utilization for energy in a traditional manner (cooking on inefficient stoves) contributes higher than 90%. Use of inefficient stoves results into incomplete combustion which produces high levels of particulate matter and carbon monoxide affecting about 2.6–3 billion people who rely on inefficient use of biomass for their cooking energy needs [43]. Studies conducted in three urban regions of Ethiopia and six cities of Tanzania indicated that high dependency on biomass used inefficiently for energy needs contributed to deforestation and climate change [44–46].

Deployment of biogas and other bioenergy types in developing countries could reduce high dependency on traditional use of biomass for energy needs [47]. Use of biomass in an unsustainable manner for energy needs has resulted in soil degradation, deforestation, further lowering of the water tables, destruction of natural habitats, and extinction of species, increased carbon dioxide emissions, increased wood fuel prices and restriction of wood from being used in other economic activities [48]. According to Zulu and Richardson [49], charcoal usage accounts for more than 80% of urban households in the sub-Saharan Africa and although it provides an alternative source of income, it undermines the production of ecosystem services, agricultural production and human health. Traditional use of biomass for cooking on inefficient stoves causes about 3 million deaths every year due to particulate matter and other gas exposure and 85% of these deaths are due to indoor air pollution [50]. Domestic biogas digesters are a promising technology which has been adopted in Asia, Africa and other parts of the world. Biogas production could replace the use of wood [51], dung and crop residues as a cooking fuel, reduce exposure to particulate matter, reduce deforestation, reduce water pollution, replace chemical fertilizer with organic fertilizer, bring about economic development and reduce energy poverty in rural areas, mitigate climate change, create employment, increase food production, act as a solid waste and wastewater treatment system [52,53]. Other benefits of biogas production may include but not limited to job creation, odor reduction and replacing of firewood and fossil fuels [54].

The objectives of this study were to estimate the biogas potential from livestock in Chitete rural settlement of Chikankata District in Southern Province of Zambia and develop a biogas model that could be adopted and implemented in rural parts of Zambia. Other objectives were to quantify environmental, social, health and safety, and economic benefits of such rural biogas supply models. To come up with this model, the Chitete Settlement of Chinkakata was used as a real case. The model would be replicable and sustainable to all rural parts of Zambia where biogas potential exists. The study involved establishing the biogas potential from livestock manure, digester sizing, establishing environmental, sanitation and health, social and economic benefits that would arise from such a model. The model looked at the practicalities of financing, feedstock sourcing and market availability of such a model. Among the benefits were the amounts and costs of firewood, dung and charcoal that would be saved as a result of using biogas, women's opportunity cost of collecting firewood, chemical fertilizer that could be replaced by organic fertilizer and the earnings that would accrue from the sale of organic fertilizer, avoided greenhouse gas emissions from chemical fertilizer application, avoided greenhouse gas emissions from firewood, charcoal and dung consumption for energy needs in a traditional manner, avoided health impacts and economic benefits. According to Reddy [55], biogas systems must not only be sustainable but also replicable to areas of similar conditions and environment. Biogas production from crop and forest residues has not been included in this study because producing biogas from these is relatively expensive as compared to use of dung [56] due to the costs for feedstock pre-treatment, long hydraulic retention times and long payback periods. This study will close data gaps that have existed for a long time in this area of study and it will form a basis (model) for biogas implementation not only in Chitete settlement but also in many other parts of Zambia where biogas potential exists. This study is unique because it is the first of its kind in Zambia and compared to other studies outside Zambia, it includes environmental, social, health and economic benefit assessment which is not the case in other studies. Most studies done in the sub-Saharan African countries like Ethiopia, Zimbabwe, Kenya, Uganda, Nigeria and Cameroon does not include the environmental assessment of avoided greenhouse gases and nitrogen losses that could be avoided [25,32,51]. The justification for using Chitete settlement was that the area has a lot of livestock and has no access to electricity like most remote parts of Zambia; the residents of the settlement use firewood, charcoal and dung to meet their daily energy needs. These are some of the pre-requisites of biogas production. It also has a similar environment and conditions like most parts of Zambia that rear livestock, thereby making it easy to replicate such a model to other such areas.

2. Methodology

2.1. Data and information

Table 1 gives the basic information about Zambia for the year 2014.

Information and data on livestock and poultry population were obtained from the Food and Agricultural Organization of the United Nations (FAO) database and journal publications on Zambia, and the number of households that are engaged in each livestock category rearing from the Central Statistics Office (CSO) and the Indaba for

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