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Original Research Article

Techno-economic analysis of small scale biogas based polygeneration systems: Bangladesh case study

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ABSTRACT

Access to electricity, clean energy, and safe drinking water services are genuine needs of the rural poor for their welfare. These needs can be addressed either individually or in an integrated approach. Biogas digesters are promising in the rural setting and integration of biogas production with power generation and water purification is an innovative concept that could be applied in remote areas of Bangladesh. This paper presents a new concept for integrated biogas based polygeneration and analyzes the techno-economic performance of the scheme for meeting the demand of electricity, cooking energy and safe drinking water of 30 households in a rural village of Bangladesh. The specific technologies chosen for the key energy conversion steps are as follows: plug-flow digester; internal combustion engine; and air-gap membrane distillation. Mass flows and energy balance, levelized cost of producing electricity, cooking gas and safe drinking water as well as the payback period of such a polygeneration system were analyzed. The results indicate that this polygeneration system is much more competitive and promising (in terms of levelized cost) than other available technologies when attempting to solve the energy and arsenic-related problems in Bangladesh. The payback period of such system is between 2.6 and 4 years.

Introduction

Background

Bangladesh is one of the world's most densely populated and least urbanized countries, and about 116 million (i.e. 72% of total population) live in rural areas [1]. About 47% of the total population has access to electricity and only 6% have access to natural gas through the national pipeline grid [2]; moreover these services remain largely unreliable. The per capita energy consumption in Bangladesh (about 180 kWh) is one of the lowest in the South Asia region [3] and the national energy demand is growing rapidly, at a rate of 10% annually [4,5]. For the case of rural populations, the energy consumption is much lower. As per the Bangladesh Rural Electricity Board, 45% of the country's villages have been electrified through connection to the national grid but, despite this, only 22% of the rural population has access to electricity [2,6]. There is no natural gas pipeline connection in rural and remote areas. The rural population traditionally uses non-commercial biomass energy sources for cooking (fuel wood, cow dung, and agricultural waste), which accounts for 62% of energy consumption [5,7]; kerosene is often employed for lighting. The 44 million tons of fuel wood that is used for cooking and heating purposes are inefficiently burned and poorly managed [7,8]. Efficiency of traditional village cooking stoves is about 5–15% [9] which leads to severe environmental problems including depletion of forest resources, severe air pollution, etc.

The combination of increasing energy demand, limited amount of natural resources available, and lack of clean renewable energy has led to a burgeoning interest in biogas technology in Bangladesh. Anaerobic digestion (AD) holds great potential for manure stabilization, sludge reduction, odor control, and energy production [10]. It provides clean and efficient fuels that can be used for several end uses, including cooking, water heating and thermally-driven cooling. Another important application of biogas is electric power generation through internal combustion engines to drive electric generators [11]. Whereas using biogas for only cooking is more common, generating electricity is relatively rare in Bangladesh, despite the fact that internal combustion engine technology is mature.

Not only lack of electricity but also safe water scarcity is threatening social and economic growth in rural areas of developing countries like Bangladesh. In the late 1970s, approximately four million shallow tube-wells were drilled to replace the traditional surface water which was highly polluted by many sources including micro-organisms and pathogens. Currently the primary source of

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drinking water for millions of rural people in Bangladesh is tube well ground water, most of which is heavily contaminated with high levels of natural occurring arsenic. Groundwater of 50 districts out of a total of 64 districts contain arsenic levels greater than the country's standard for shallow tube-well drinking water (50 μg/L), and in around 60 districts ground water is contaminated with arsenic levels greater than WHO recommendations (10 μg/L) [12]. This has resulted in a major public health crisis with as many as 70 million people possibly at risk [13]. The rural and poor in the inland and coastal zones of Bangladesh are the ultimate victims of arsenic poisoning from groundwater consumption. The concentration of arsenic in ground water ranges from less than 0.25 μg/L to more than 1600 μg/L [14]. Additionally, in coastal regions people face more challenges due the salt intrusion in surface water and shallow aquifers.

While the problem of arsenic contaminated drinking water in shallow tube-wells is relatively well known, challenges remain in the widespread implementation of low-cost and effective arsenic removal strategies in Bangladesh, especially in rural and remote areas. One alternative is to use surface water, but this carries the risk of serious microbiological pollution. The treatment facilities needed for that often exceed local financial resources and operational capacity. Moreover, 95% rural population drinks shallow tube-well ground water and people prefer not to drink treated surface water because of its taste and smell [15].

Efforts have been made by the government, as well as by non-governmental and international organizations, to address the widespread rural energy problem and to mitigate the catastrophe of arsenic contamination in drinking water: various programs support the dissemination of biogas digesters, and filters and simple chemical treatment packets have been distributed in an attempt to handle the arsenic problem. These efforts have not been very successful in reaching the poorer and more remote sections of the country, largely due to limitations in affordability and technical and economic viability. The efforts made so far remain fragmented, and a holistic approach is often missing in addressing the multiple service needs of the rural areas (clean cooking, energy, electricity and safe drinking water). Polygeneration – an energy system capable of producing several useful energy services from one or more primary energy inputs – can play a critical role in this context. A few researchers [16–22] have been exploring different integrated polygeneration systems in order to achieve better energy efficiency compare to conventional power plants by recovering waste heat through additional cooling and heating. Of these studies only one includes a thermo-economic analysis [22]. Clearly there is scope for investigating new concepts for tackling this multifaceted problem.

Objectives and scope

This paper presents an innovative energy and drinking water solution via a small scale biogas based polygeneration system designed for deployment in rural Bangladesh. The concept encompasses a gas engine and cooking stove integrated with a digester; waste heat from the engine drives a thermally-driven water purifier (membrane distillation unit). The study estimates the size and cost of a biogas based polygeneration system, its feedstock requirements and the necessary outputs to meet the cooking energy, electricity and safe drinking water demands. For the purpose of the analysis, the investigation has considered all these needs for a small village community of 30 households in rural Bangladesh. Primary system inputs are cattle dung and contaminated water, with biogas, electricity, safe drinking water, and fertilizer are primary outputs. The study estimates the levelized cost of biogas and electricity generation and production cost of clean water, further augmented with a sensitivity analysis to observe the impact of uncertainty in key assumption and design parameters on cost. The payback period and IRR are determined in order to examine the financial feasibility of such polygeneration technologies. Primary end-user issues have been included by direct consultation with local stakeholders.

Background: digesters in Bangladesh

Livestock such cattle, buffalo and goats are common in Bangladeshi rural areas, but cow dung is the most easily available and has been employed as both fertilizer and fuel for direct burning. Anaerobic digestion allows for much higher conversion efficiency, about 55%, whereas direct combustion yields efficiencies of only 10% [23]. Gas production rates are around 0.04 m^3 gas per kg dung feedstock for psychrophilic conditions (without digester heating, fixed dome type digester) [24]. According to the Infrastructure Development Company Ltd. (IDCOL), the total technical potential of domestic biogas plants in the country is 3 million units. It is estimated that about 30 billion m^3 of biogas could be obtained from the livestock residues of the country, equivalent to 1.5 million tons of kerosene (which is currently the principal fuel for lighting in rural areas) [25].

Data for annual livestock production in Bangladesh in 2010 were obtained from Faostat 2012 [26] and presented in Table 1. It can be seen that the livestock annual average growth rate from 2000 to 2010 is 2.3%. The FAOSTAT data is quite consistent with national data.

Up to now, more than 40,000 biogas plants (mostly Chinese dome type digesters) have been installed by different NGOs under the National Domestic Biogas and Manure Program (NDBMP) of IDCOL, the Sustainable Energy for Development (SED) Program of the German Technical Cooperation (GIZ), the Netherlands Development Organization (SNV) and other government organizations such as the Local Government Engineering Department (LGED), the Bangladesh Council of Scientific and Industrial Research (BCSIR) [27]. Over 3500 units have been constructed in poultry farms in Bangladesh [28]. Most of the units are family sized and are used only for cooking purposes. As shown in Fig. 1, the number of biogas digesters increased dramatically in the mid- to late-2000's. IDCOL will introduce 100,000 biogas plants in rural areas across the country by 2016 [25].

Arsenic removal technology and membrane distillation

Comprehensive investigations [29–33] have been carried out over the last 40–50 years on removal of arsenic from ground water. Conventional technologies like adsorption, chemical coagulation–precipitation, and ion-exchange have been established as the broad technology options of water purification. Major drawbacks of these conventional processes over membrane processes are the requirements of multiple chemical treatments, pre- or post-treatment of drinking water, skilled operation, different arsenic ions (As(III) and As(V)) removal rate efficiency, high running and capital cost and more importantly, regeneration of medium and handling of arsenic contaminated sludge. Membrane distillation (MD) could be a promising novel process that can be adapted for water purification effectively in rural areas of developing countries. It is a thermally driven separation process in which only vapor phase compounds (water and possible volatiles) from hot feed pass

Table 1
Major livestock in Bangladesh in 2010 (head count in million) [26].

Cattle	Buffalo	Goat	Sheep	Poultry
23.05	1.35	50	1.82	270.7