Renewable and Sustainable Energy Reviews 90 (2018) 982–991

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Decentralized anaerobic digestion systems for increased utilization of biogas from municipal solid waste

Chukwunonso Chinedu Anyaoku[a,*], Saeid Baroutian[b]

[a] Department of Engineering Science, Faculty of Engineering, University of Auckland, UniServices House, Level, 3/70 Symonds St, Grafton, Auckland 1010, New Zealand
[b] Department of Chemical and Materials Engineering, Faculty of Engineering, University of Auckland, Building 529, 2-6 Park Avenue, Grafton, 1023 Auckland, New Zealand

ARTICLE INFO

Keywords:
Anaerobic digestion
Biogas
Distributed energy
Innovation
Organic fraction of municipal solid waste

ABSTRACT

Biogas may be able to compete favorably with cheaper fossil fuels for domestic purposes if anaerobic digestion systems are used for processing the organic fraction of municipal solid waste (OFMSW) in a decentralized manner and within an integrated solid waste management scheme. To harness this opportunity, this study reviews how a typical integrated solid waste management system (ISWM) may be reconfigured into one with lower operation costs and minimal GHG emissions. First, four literatures which conducted various environmental analyses on several ISWM scenarios for municipal solid waste management were reviewed to determine which ISWM among them had the lowest quantity of greenhouse gas (GHG) emissions in CO_2eq. Then, a simplified comparative economic analysis was conducted on the operation strategies of five different commercial solid-state anaerobic digestion (SS-AD) technologies. This economic analysis was then followed with frugal recommendations on how best an SS-AD system can be incorporated into the 'least GHG emitting' ISWM to lower the operational costs of the ISWM system. The final ISWM superstructure recommended by this study included a centralized section for commercial MSW waste, and a decentralized section primarily for residential MSW waste, and the superstructure was recommended for densely poulated urban areas. Furthermore, the decentralized section of the ISWM superstructure included the collection of source-sorted waste from households, decentralized storage for collected recyclables and digestate, and the sale of biogas exclusively as domestic cooking gas. Innovative design and operational modifications proposed for the decentralized SS-AD system were: modular and detachable digester cells for managing digester bed failure, and a vertical stacking design for achieving compactness and scalability for the digester.

1. Introduction

Landfills are the third largest anthropogenic source of methane (CH_4) emissions: they contribute about 11%, just behind those from enteric fermentation of livestock (27%) and fossil fuels (33%) [1]. Furthermore, CH_4 emissions from landfills are expected to grow from their 2005 levels of 794.0 $MtCO_2e$, to 959.4 MtCOe by the year 2030 [2]. These CH_4 emissions are caused by the natural decomposition of the organic fraction of municipal solid waste (OFMSW) contained in over 300 million tonnes of municipal solid waste (MSW) dumped at landfills every year globally [1,3]. OFMSW, though with varying definitions globally, is generally considered to include food and garden wastes [3,4], and its composition when collected could vary from 28% in high income countries to 64% in low income countries [3]. Processing OFMSW with thermochemical conversion technologies such as combustion and gasification may be unsuitable because of the high moisture content of its food waste (FW) sub fraction [5]. Nevertheless, OFMSW may be suitable for processing by anaerobic digestion (AD) technology which can convert it to biogas (a fuel) and digestate which is a nitrogen-rich compost substance. Therefore, AD presents the most sustainable technology for processing OFMSW [4]. Regardless of these benefits of AD, the technology has had relatively low levels of penetration globally. As cases in point, biogas production by AD in the US and Asia has been hampered by the availability of cheap fossil fuel [6]. In Europe however, the use of AD has been incentivized by higher energy prices and government incentives, and this has resulted in a much wider adoption of this technology there compared to other world regions [7,8].

From the energy market situation pointed out above, one way of increasing the adoption of AD technologies would be to reduce its cost of operations, at least enough to make its end products like biogas more affordable than fossil fuels. One strategy to achieve this in MSW

* Correspondence to: Plot 445, FHA, Lugbe, Garki Area 1, 90024, Abuja, Nigeria.
E-mail address: cany183@aucklanduni.ac.nz (C.C. Anyaoku).

https://doi.org/10.1016/j.rser.2018.03.009
Received 11 March 2017; Received in revised form 4 October 2017; Accepted 9 March 2018
1364-0321/

management is to utilize a decentralized approach in integrated solid waste management (ISWM). A decentralized operation of ISWM systems could minimize waste transportation costs, and maximize the end product benefits for the local community. Furthermore, as a consequence of the afore mentioned benefits, a decentralized operation could increase public acceptance of the decentralized facilities [9,10]. However, AD technology lends itself much better to a decentralized operation if implemented as a solid-state anaerobic digestion technology (SS-AD) technology: SS-AD systems require less reactor space, less water, and less heat energy resources than wet AD systems because SS-AD digesters operate with more total solid (TS) content (i.e. TS content 15–50%) than wet digesters (i.e TS content < 15%) [11–13]. However, the operation of many of today's commercial SS-AD systems in urban areas, with their original centralized operation strategy, may be undermined by socioeconomic constraints such as limited water resources and inadequate road transport infrastructure likely brought about by rapidly increasing urban populations or low density urban sprawls [14,15]

To address this challenge, this study reviews some ISWM systems which were of interest to some authors, and how the best of these systems may be adapted for even lower-costing operations and minimal environmental impact. Once this goal is achieved, it is expected to increase the profitability of each of the select ISWM system's processes, including the production of biogas with decentralized SS-AD systems. This increase in profits should in turn help managers of SS-AD systems lower the cost of the biogas they produce thereby making it more affordable and competitive in the local energy market for domestic use. In view of the workability of this strategy, several studies containing environmental impact and economic anlysis studies on ISWM systems were reviewed. Then, the 'least GHG emitting scenario' in each of these studies (i.e. scenarios whose ISWM systems had the smallest GHG emission when compared with their respective alternatives) were compared to determine the overall least GHG emitting scenario among them. This scenario was then referred to as the ISWM system template, which would later have a decentralized SS-AD system incorporated into it in order to explore ways the ISWM template's operation costs can be further reduced while minimizing its negative environmental impacts. However, unlike most of the reviewed literatures which considered a single type of AD technologies for all their respective analysed scenarios, this study analysed five different commercial SS-AD technologies and their comparative operational cost implications. Finally, the SS-AD system with the most frugal operation techniques was selected, and some design modifications that may help the SS-AD system to operate more profitably within typical spatial constraints in urban environments were proposed. The findings from this review is considered most beneficial for urban areas with inadequate infrastructure for waste management, and with low to medium income residents who may not be able to afford traditional centralized ISWM services.

2. Methodology

The aim of this review may be considered as being the same with that of a product development process, which is, to transform a market opportunity into a product for sale [16]. Therefore, a concept development phase, which is typically the first principal step in a product development process [16,17], was initiated in line with the overarching goal of the study, which is: to conceive an ISWM system with minimal operation costs and minimal GHG emissions. The basic questions usually addressed in the concept development phase are:

a. What are the target values of the product attributes?
b. What will the product concept be?
c. What variants of the product will be offered?
d. What is the product architecture?
e. And, what will be the overall physical form and industrial design of the product? [16]

Questions (a) and (b) have already been answered by the stated overarching goal. However, questions (c), (d) and (e) will be answered with the results from an economic and environmental impact analysis. All results of the economic and environmental impact analysis in this study were deduced from analysing data contained in reviewed literature.

2.1. The environmental analysis component

This environmental analysis aimed to select an ISWM system, from the scenarios analyzed in the reviewed studies, that had the least GHG emmissions. Four studies were reviewed for this analysis: two based on case studies in a developed country and two on case studies in a developing country. Three of these literatures utilized a life cycle assessment (LCA) analysis, while one of them depended on its own developed mathematical model. A life cycle assessment (LCA) was considered important tool in providing insight in this study since it assesses the environmental impacts of a product, activity or service throughout every stage of its life cycle: from raw materials extraction, through processing, manufacturing, distribution, use, possible reuse/recycling and onto final waste management [18]. Also, this analysis limited its parameter of interest in its environmental analysis to GHG emissions measured in carbon (IV) oxide equivalents (CO_2eq). Therefore, each scenario with the least GHG emission in their respective literature was noted and compared with other least GHG emitting scenarios from other reviewed studies. Then, the absolute least GHG emitting scenario among them was picked and refferred to as the ISWM template for this study. This ISWM template then served as the starting point to explore strategies that could further minimize the ISWM template's operation costs without causing an increase in the system's negative environmental impact, including how to incorporate decentralized AD systems into the ISWM system. While this study recognizes that each operation cost of each least GHG emitting scenario was not necessarily the one with the least operating costs in their respective studies, this study assumes that the operational costs of the ISWM setups of these scenarios were low enough to yeild sustainable profits to keep their respective ISWM systems operational. Furthermore, this study put a priority on first minimizing GHG emissions before minimizing the operational costs of an ISWM system, as long as the system remains profitable to operate.

2.2. The economic analysis component

The goal of this economic analysis was to further minimize the operational costs of the ISWM template, particularly as it pertains to minimizing the cost of producing biogas. Already, a major strategy to achieve this goal has been identified: to incorporate decentralized SS-AD systems into the ISWM template. Although this study acknowledges other avenues for minimizing costs in an ISWM system (e.g. using more energy efficient processes for each waste management step), rather than attempting to minimize the operational costs of each individual process in the ISWM template, this study will focus on the minimizing the operational cost of operating an SS-AD system within the template. This is because the SS-AD process, if made the primary process for transforming the typically largest fraction of MSW in many countries (i.e., OFMSW), could have an overwhelming positive impact on the overall costs of operating the other processes of its host ISWM system, particularly because the profitable extraction of OFMSW from mixed MSW could create cleaner and more reliable suplies of feed for other ISWM processes. In light of this benefit, the economic analysis of this study will strive to:

a. Select the most frugally operating SS-AD system for the ISWM template.
b. Identify design modifications that can lead to reduced operation costs of the selected SS-AD system, and increase their suitability for decentralized operations.