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Design of an organic waste power plant coupling anaerobic digestion and solid oxide fuel cell technologies

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ABSTRACT

The preliminary design of an organic waste power plant utilizing both anaerobic digestion and solid oxide fuel cell (SOFC) technologies is presented along with a review of these technologies. Food waste and sewage sludge from a mid-sized Canadian municipality were modeled as feedstock for anaerobic digestion. The biogas quality and quantity produced from the digestion process were determined by modeling the municipal waste's chemical composition and chemical oxygen demand (COD) content. Overall, between 480 kW and 1410 kW of electrical power can be produced from the SOFC system fueled by the biogas. The compatibility of these two technologies is evident and the major challenges and benefits associated with implementing this concept are discussed. This work demonstrates that an organic waste power plant is a sustainable solution to waste management and power production.

1. Introduction

Energy production and waste management are growing issues in modern society [1,2]. Traditional energy production relies heavily on non-renewable resources which are damaging to the environment while the majority of waste management practices do not use the potential energy stored in organic wastes. It is therefore desirable to develop a sewage and municipal waste disposal process that can cleanly harness the energy contained in organic wastes. Coupling existing anaerobic digestion technology with solid oxide fuel cells (SOFCs) is a unique approach to solving these problems. By creating an organic waste fueled power plant using these two technologies, electricity, heat, and compost can be produced from organic wastes while reducing the emission of greenhouse gases and avoiding the release of harmful pollutants such as methane, nitrous oxides, and sulphur oxides.

Organic wastes can create a number of environmental and health hazards when contained in landfill. Leachate from organic materials can cause problems such as ground water contamination while landfill gasses created by organics decomposing contribute to greenhouse gas (GHG) emissions. In the literature [3,4], diversion of organic materials from landfill sites is commonly proposed as a solution to these health and environmental impacts. However, in 2012, over 65% of municipal solid wastes in Canada and the United States were disposed of in a landfill [5,6]. Diverting organic wastes from landfill sites will extend landfill life and decrease health and environmental impact through reduction of harmful leachate and emissions [3,4].

A number of cities, such as Guelph, Ontario, Canada, have adopted source separation methods for diverting organic wastes from landfill [3]. However, many of these municipalities do not take full advantage of the biogas production that could be achieved through anaerobic digestion of organic waste material. This is especially true of municipal waste water treatment plants (WWTPs). In the United States, less than 10% of municipal WWTPs produce biogas for beneficial use, yet 6.5 million tonnes of energy dense sewage sludge are generated by the country annually [7,8]. There are currently very few options for disposal of sewage sludge and those methods are both costly and strictly regulated due to the potential for contamination and pollution [9]. One alternative method for disposal would be to use anaerobic digestion, which converts the municipal waste to biogas. This disposal method has the added benefit of destroying pathogens contained in the waste material, leaving nutrient rich compost which can be safely used as fertilizer.

Biogas produced through an anaerobic digestion process is primarily methane. This hydrocarbon fuel, alongside coal and oil, is often combusted to produce electricity or flared [10]. In 2008, the electrical power generation sector was the largest GHG contributor in Canada, producing 16% of all Canadian GHG emissions [11]. In the United States, the electrical power requirements of waste water treatment

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alone contribute 21 million tonnes of GHG emissions annually [10]. Instead of combusting the obtained biogas from digestion of organic wastes, the raw biogas can be refined into fuel for an SOFC system. SOFCs can efficiently produce electricity and heat from the electrochemical combination of biogas and oxidant, effectively offsetting the GHG emissions associated with WWTPs [12].

Provided any contaminants in the biogas, such as hydrogen sulphide, are removed, an SOFC system could continuously provide clean electricity from anaerobic digestion of municipal wastes. Other systems that couple anaerobic digestion with hydrogen fuel cells, such as the proton exchange membrane (PEM) fuel cell, require hydrogen fuel to be derived from the produced biogas through a complex process [13]. It is also necessary to remove carbon monoxide from the biogas to prevent poisoning of PEM fuel cell systems [14]. These fuel processing steps require additional infrastructure and energy, making the SOFC a more efficient and cost effective option for pairing anaerobic digestion and fuel cell technology. SOFCs can also operate using the variable composition of the biogas, whereas internal combustion engines require a significantly higher amount of tuning to run effectively with varying fuels.

An anaerobic digestion/fuel cell (ADFC) system fueled by municipal sewage and organic wastes provides both waste management and energy solutions simultaneously while remaining environmentally friendly. An ADFC can be considered a carbon neutral power source because the biogas produced from waste streams is naturally occurring; anaerobic digesters in this context are simply used to speed up the digestion process of the bacteria. For this reason it can be assumed the energy produced by an ADFC system would directly offset any greenhouse emissions incurred on a traditional power plant in its place.

The concept of an anaerobic digestion-solid oxide fuel cell (ADFC) system has only been evaluated a few times in literature [12,15–17]. Previous work by Van Herle et al. [17] present data on multiple biogas sources, such as landfills, and provide a case study of a small scale SOFC co-generation system running on biogas. In their study, modeling software (BELSIM) is used to model the fuel reforming reactions and SOFC thermodynamics involved in utilizing different biogas sources. The results demonstrate that the concept is applicable on scales from individual farms with 10 kW systems to landfill sites with 1 MW systems. But despite providing a lengthy discussion on design and performance parameters of the model SOFC system, Van Herle et al. do not discuss the equally important design aspects of anaerobic digestion. This theme continues in the literature [12,15] where anaerobic digestion is not manipulated or controlled to produce an optimal biogas for use in SOFC applications. Instead, the more common approach to researching ADFC technologies is to start with an approximate biogas composition and then model or test biogas reforming and model SOFC thermodynamics from there [15,18–21].

In contrast, Papurello et al. [16] recently completed a pilot scale study of a waste-to-energy system which successfully couples anaerobic digestion of organic wastes from municipal sources and SOFC technologies. In their work, they cite three years of anaerobic digestion development to obtain a high methane concentration in the biogas. However, their system achieved a digester efficiency of 20% and had a retention time of 40 days. In addition, their system achieved an overall electrical efficiency of 17%. Their experimental research suggests that coupling AD and SOFC technologies is feasible, but points to the need for optimization of the fuel cell system [16].

More recent work on coupling these two technologies by Lackey et al. [15] focuses on UniSIM modeling and experimental operation of an SOFC operating with biogas from waste water treatment plants but does not include a discussion of waste processing or anaerobic digestion technologies as developed in Papurello et al's pilot scale system. The contribution by Lackey et al. helps optimize the SOFC performance side of ADFC technologies which is also intensively studied in the literature [12,15,17–25]. To fully develop the combined ADFC system, unification of both anaerobic digestion and SOFC fields is needed to optimally couple these two technologies together in a system such as the one investigated by Papurello et al. [16].

Having reviewed the literature, the authors believe this is the first known presentation of a simplified ADFC system model which cumulatively explains the diverse breadth of the technology (organic waste processing, anaerobic digestion, biogas production, and SOFC performance) to demonstrate the benefits and feasibility of the entire ADFC process. Literature review of these topics is used to provide a meaningful commentary on the design and implications of ADFC systems.

1.1. Anaerobic digestion

Anaerobic digestion is the process of microorganisms decomposing organic compounds in the absence of oxygen [9]. The products of anaerobic digestion are biogas, which primarily consists of methane, carbon dioxide, and digestate [26]. The digestate from the anaerobic digestion process can be used as fertilizer for the agriculture industry [26]. The quality of the biogas and digestate depend on the type of material being digested, the pre-processing of that material, and the conditions in which the digestion is taking place. Inorganic material remains effectively undigested if included in the process [27].

The anaerobic digestion process consists of three main stages: hydrolysis; fermentation; and methanogenesis. During hydrolysis, insoluble organic matter is broken down to make soluble organic substances such as amino acids, fatty acids, and sugars [28,29]. Fermentation consists of two sub-processes, acidogenesis and acetogenesis, which break down the products of hydrolosis into alcohols, acetic acid, and gas containing H_2 and CO_2 [29–31]. Two main methanogenic bacteria groups produce methane during methanogenesis. One group of bacteria splits two acetate molecules to form methane and carbon dioxide [29–31] while the remaining group uses hydrogen as an electron donor and carbon dioxide as an electron acceptor to produce methane [29]. The acetate reaction is the primary reaction that produces methane due to the low hydrogen production rate in the fermentation process [27].

1.2. Solid oxide fuel cells

Fuels cells are energy conversion devices that convert the chemical potential energy of a fuel into electricity without the need for combustion. They can achieve overall efficiencies exceeding 60% in combined heat and power systems and they do not emit the harmful GHGs, such as nitrous and sulphur oxides, that combustion does [14,32]. There are multiple types of fuel cells, most of which rely on pure hydrogen for fuel. SOFCs are superior to other designs in the way that they can handle a wide range of hydrocarbon fuels, such as methane and carbon monoxide without the use of expensive catalysts such as platinum.

The electrochemical combination of the fuel with an oxidant produces electrical current (W_e), waste heat (Q), and water. There are significantly less pollutants released in the process compared to traditional combustion reactions used to drive electrical generators [33]. By connecting multiple cells in series, the overall voltage can be increased and SOFC stacks can be built for different scale applications. The heat rejection from the fuel cell yields opportunity for co-generation which would further increase the overall efficiency of the system.

1.3. Coupling anaerobic digestion and SOFC technology

The process of converting organic waste into biogas can be controlled through the use of an anaerobic digester under specific operating conditions. The inputs to the digester are heat, water, and pre-processed organic waste. During the digestion process appreciable quantities of biogas are produced. The process provides an effective solution for organic waste management while the biogas can be captured and used as fuel and the digestate can be used as a nutrient