Available online at www.sciencedirect.com

SciVerse ScienceDirect

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

Design of a combined heat, hydrogen, and power plant from university campus waste streams

J. Daniel Spencer [a], Jennie M. Moton [a], William T. Gibbons [b], Kyle Gluesenkamp [a], Islam I. Ahmed [a], Andrew M. Taverner [c], Diane McGahagan [a], Meron Tesfaye [b], Chetali Gupta [b], Richard P. Bourne [a], Viviana Monje [b], Gregory S. Jackson [a,*]

[a] Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA
[b] Department of Chemical Engineering, University of Maryland, College Park, MD 20742, USA
[c] Department of Cell Biology and Genetics, University of Maryland, College Park, MD 20742, USA

ARTICLE INFO

Article history:
Received 2 February 2013
Accepted 2 February 2013
Available online 7 March 2013

Keywords
Molten carbonate fuel cell
Hydrogen
Combined heat and power
Waste energy conversion
Polygeneration

ABSTRACT

This paper presents analysis of a combined heat, hydrogen, and power (CHHP) plant for waste-to-energy conversion in response to the 2012 Hydrogen Student Design Contest. Our team designed the CHHP plant centered on a molten carbonate fuel cell (Fuel Cell Energy DFC-1500) fueled by syngas derived primarily from an oxygen-fed municipal waste gasifier. Catalytic methanation and supplemental utility natural gas increase the fuel methane content to meet the DFC-1500 fueling requirements for maintaining stack thermal energy balance. Internal reforming converts excess fuel from the fuel cell to an H_2-rich stream, which is purified downstream in a pressure-swing adsorption system. The separated H_2 (1000 kg per day) is compressed for storage to provide fuel for a campus fleet of PEM fuel cell buses. The system provides more than 1.1 MWe for the campus grid with approximately 20% of the fuel cell power used for H_2 compression and running the plant. Heat recovery steam generators provide steam for the methanation reactor and 0.4 MW of thermal energy for district heating or steam turbine-driven chillers. Cost analysis indicates that the system requires incentives for economic viability with current estimated operating costs, but advances to reduce capital expenses of comparable urban waste-driven CHHP systems can make them attractive for future implementation.

1. Introduction

The 2012 Hydrogen Student Design Contest provided a venue for exploring the use of municipal solid waste (MSW) and organic waste from university campuses, surrounding municipalities and industries as a fuel source for combined heating, hydrogen, and power (CHHP) to the campus and local community. The CHHP system design was centered on a molten carbonate fuel cell (MCFC) stack (DFC-1500 from Fuel Cell Energy in this study), which has demonstrated successful operation with direct feeds of biogas and natural gas for several applications [1,2]. The high-temperature (~650°C) operation of the MCFC allows internal reforming of small hydrocarbons (usually methane/natural gas), which provides an endothermic reaction to remove some of the excess heat from the electrochemical oxidation of fuel in the MCFC and thereby maintaining the stack near its desired operating temperature[2,3]. The heterogeneous reactions in the MCFC

* *Corresponding author*. Current address: Dept. of Mechanical Engineering, Colorado School of Mines, Golden, CO 80403 USA. Tel.: +1 303 273 0409; fax: +1 303 273 3620.
E-mail address: gsjackso@mines.edu (G.S. Jackson).
0360-3199/$ – see front matter
http://dx.doi.org/10.1016/j.ijhydene.2013.02.021

require that the fuel source have adequate methane or hydrocarbon content to maintain the fuel cell energy balance and that the gasified fuel be cleaned of impurities such as siloxanes [4,5] and sulfur-containing compounds [6,7] that can lead to anode poisoning and unacceptable degradation rates of the fuel cell performance. As such, successful integration of an MCFC power plant with a waste-gas production process requires significant, careful design of upstream fuel processing and purification.

Converting municipal and organic waste streams to a feedstock amenable for high-temperature fuel cells requires waste gasification using an oxidizing agent (steam, air, oxygen, and/or plasma) to produce a fuel-gas stream. Research and development has led to various commercial approaches for biomass and MSW gasification to produce H_2-rich syngas as presented in detail in recent studies and reviews [8–10]. The polymeric nature of much MSW (plastics and paper) requires high temperatures for gasification through exothermic air-fed or oxygen-enriched gasification, indirectly fired steam gasification, or energy-intensive plasma gasification. While steam gasification can provide the highest H_2 content and exergetic efficiency for the gasification process [11], it can require large capital investments for indirect firing to supply heat for the endothermic steam gasification reaction. Exothermic air-gasification provides a more economical and flexible method for converting waste to synthesis gas, but the resulting syngas stream can have as much as 60% N_2 and thus, very low energy densities (<7 MJ/m^3) [8]. O_2-enrichment of the air for gasification mitigates the N_2 dilution problem, and commercial advances in oxide-ion-transport membranes [12] and pressure-swing adsorption systems [13] provide approaches for high-purity O_2 separation without the complexity and scales required for cryogenic plants. Plasma gasification provides an alternative that can reduce the need for waste prescreening, but the high electric power demands for plasma generators and their intense maintenance cycles limit this technology [14,15] to value-added applications where space and waste removal are at a premium.

High-temperature fuel cells, both MCFC [16–19] and solid-oxide fuel cells (SOFCs) [11,20–22], have been explored for integration with waste gasification. At the MW scale relevant for MSW processing, the Fuel Cell Energy MCFC technology offers more flexibility with respect to fuel content than recently commercialized SOFCs, and MCFCs have been operating successfully in food waste and sewage processing where the solid feeds and wastes are more steady and uniform than typical MSW streams. The challenge with high-temperature fuel cell technologies remains costs (≫$1000/kWe installed), and a very recent study on MCFC costs for biogas applications suggests that these high costs keep payback periods well over 5 years and likely over 10 years depending on uncertain economic situations [23]. As such, the challenge remains to ensure optimal value of the plant outputs, and continued support of research and development that will drive the costs down of the fuel cell stack, waste gasification, and supporting equipment.

The Hydrogen Student Design Contest pushed the design analysis to look beyond just waste processing and fuel cell integration to consider H_2 recovery from the fuel cell exhaust as a means to increase the output value of the plant. Recovering excess H_2 fuel has been proposed at large central power-plant scales as part of the Future Gen program sponsored by the U.S. Dept. of Energy [24]. H_2 recovery provides a mechanism for adjusting the fuel cell operating point to provide more or less power or H_2 depending on the demands. Of course, if the H_2 is used for low-temperature PEM fuel cells for transportation applications (as in this study), purification and compression will be required. Pressure-swing adsorption (PSA) systems provide the most commercially viable purification systems at the MW scale to extract H_2 from syngas over the range of compositions expected from a fuel cell exhaust [25,26].

A CHHP plant based on waste gasification, high-temperature fuel cells, and downstream H_2 recovery requires significant thermal integration in order to optimize system efficiency. Thermal integration is complicated by the wide range of temperatures required throughout the plant ranging from the high-end (ca. 800–900 °C for the waste gasifier) down to near ambient temperatures for the hydrogen separation in the PSA bed. The efficient and cost-effective recovery of heat, both for internal purposes as well as for any external heating or heat-driven processes, strongly impacts the value proposition of the plant.

This paper presents the basic design and analysis of a CHHP system fueled in part by waste from the UMD campus and surrounding municipalities. The availability of the UMD campus power plant and heating and cooling system as well as a locally maintained campus bus fleet for possible upgrades to H_2-fueled PEM fuel cell buses make the campus an ideal place for exploring the value proposition of CHHP from urban waste streams. As indicated below, the economic viability of the system is highly sensitive to the cost of the major CHHP components (such as the gasifier and fuel cell stack), the operating costs, and legislated economic incentives. The process analysis does not address concerns regarding plant durability, but it provides a basis for assessing feasibility of CHHP at the university campus scale.

2. Methodologies

2.1. *Waste stream analysis*

Assessment was performed on the locally available waste streams from the University of Maryland campus and the surrounding City of College Park with the intent to characterize the amount of fuel energy available in a given waste stream. Masses of the relevant waste streams were obtained from the University Recycling and Solid Waste Program and the City of College Park Department of Public Works. Detailed compositional data was provided for recycled materials on campus (in terms of mass of paper, plastic, glass, and metals), which comprises approximately 20% of the usable waste from the University and City together. On the other hand, only total masses were provided for MSW from campus and the City of College Park and the recycled waste from College Park. Therefore, compositions for the MSW and municipality recyclables were adapted from studies of recent municipal solid and organic wastes of a similar university community. Glass, metals, and other wastes not amenable for gasification