Technical note

Hydrogen production and End-Uses from combined heat, hydrogen and power system by using local resources

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Abstract

To address the problem of fossil fuel usage at the Missouri University of Science and Technology campus, using of alternative fuels and renewable energy sources can lower energy consumption and hydrogen use. Biogas, produced by anaerobic digestion of wastewater, organic waste, agricultural waste, industrial waste, and animal by-products is a potential source of renewable energy. In this work, we have discussed Hydrogen production and End-Uses from CHHP system for the campus using local resources. Following the resource assessment study, the team selects FuelCell Energy DFC1500™ unit as a molten carbonate fuel cell to study of combined heat, hydrogen and power (CHHP) system based on a molten carbonate fuel cell fed by biogas produced by anaerobic digestion. The CHHP system provides approximately 650 kg/day. The total hydrogen usage 123 kg/day on the university campus including personal transportation applications, backup power applications, portable power applications, and other mobility applications are 56, 16, 29, 17, and 5 respectively. The excess hydrogen could be sold to a gas retailer. In conclusion, the CHHP system will be able to reduce fossil fuel usage, greenhouse gas emissions and hydrogen generated is used to power different applications on the university campus.

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1. Introduction

The Missouri University of Science and Technology (Missouri S&T) campus in Rolla, Missouri, USA is a relatively small campus with 1.15 km² and approximately 6500 students on campus. Biogas produced by anaerobic digestion of wastewater, organic waste, agricultural waste, and industrial waste is a potential source of renewable energy. Treated biogas can be used to generate CHHP using a molten carbonate fuel cell. The paper investigates the use of a CHHP system at (Missouri S&T) campus, and we have discussed the Hydrogen production, recovery, cleaning, and End-Uses on the university campus from CHHP system by using local resources. The hydrogen generated by the CHHP system is used personal transportation, backup power, portable power, and mobility/utility applications at various locations on the campus [1–4]. The research presented in this paper was performed as part of the 2012 Hydrogen Student Design Contest. In addition, the performance assessment of the CHHP system has higher efficiency than other distributed generation plants of similar size [5,6]. The CHHP system attains ultra high efficiency about 60–75% power and reducing gas [1].

2. Resource assessment

2.1. Feedstock source identification

During the assessment, “locally available feedstock” was defined as one which is within 20 km of Rolla. The largest source of locally available feedstock is MSW averaging 60 tons/day. Of this, approximately 33% is organic waste including 17% food waste. The campus plans to partner with the City of Rolla and will start an “Organic Waste Collection Program” to collect organic waste. Currently, the city offers residential curbside collection of recyclable materials at no extra cost.

Potential feedstock from the campus includes food waste and sanitary sewer. Food waste collected daily is mixed with the trash and the sanitary sewer and is connected to the city’s main sewer...
Nomenclatures

AGO  anode gas oxidizer
AOG  anode outlet gas
CHHP combined heat, hydrogen and power system
CHP combined heat and power
DFC direct fuel cell
GHG  greenhouse gas
HEX.W.G heat exchanger water and gas
UPS  uninterruptable power supply

lines. Methods for feedstock collection, transportation, and storage were also identified and are tabulated in Table 1 [7,8].

3. Experimental procedure

3.1. DFC® technology status

FuelCell Energy offers three DFC® products; the DFC 300 T™, DFC 1500™, and DFC 3000™, which are 350 kW, 1.4 MW, and 2.8 MW, power plants, respectively. The DFC® 1500™ matches up well with the needs of a wastewater treatment plant, or a food processing facility where methane produced by anaerobic digestion can be efficiently utilized to produce electricity.

The DFC® technology offers higher net electrical efficiency and a cleaner exhaust stream when operating on biogas from an anaerobic digester than any competing conventional technology such as reciprocating engines or gas turbines. The DFC® systems also have a good heat-to-power ratio for support of digester operations.

The design discussed in this paper has three major systems: (i) anaerobic digestion system, (ii) CHHP system consisting of a DFC1500™ fuel cell unit, and (iii) hydrogen compression, storage, and dispensing system [1–3].

3.2. Anaerobic digestion system

Digester and biogas production are shown in Fig. 1(a)[2,3,9]. Biogas from the anaerobic digestion is stored in a buffer tank which supplies biogas to the gas treatment system. The treatment system uses pressure swing adsorption (PSA) technology to separate methane present in the biogas [10,11]. The design included the PSA unit for the following reasons [1–3,8]:

3.3. DFC1500™ FuelCell power plant

The anaerobic digester system will be able to supply 90% of fuel for the DFC1500™ unit from locally available feedstock. The remaining 10% fuel required will be purchased from the utility company. In order to accommodate the fluctuations in gas quality, the natural gas used in the design is assumed to contain 98% methane and 2% carbon dioxide (with an average heating value of 37 MJ/m³). Fig. 2(a) shows the reactions taking place inside the fuel cell [1–3,7].

3.3.1. AOG calculations

The anode outlet gas calculations are made based on the AOG composition calculation document provided by FuelCell Energy [16]. It is assumed that all methane entering the DFC® unit is internally reformed and converted to hydrogen and that only 65% (the fuel utilization rate) of the H2 produced is reacted at the anode to produce electricity. In order to reflect the AOG composition, it assumed that One third of the 35% hydrogen produced is back-shifted to produce H2O and CO. Based on these assumptions and the processes taking place inside the fuel cell, the following Equations (1)–(5) for every 1 mol of methane (CH4) entering the anode side are obtained.

Internal reforming:

\[ \text{CH}_4 + 2\text{H}_2\text{O} \rightarrow 4\text{H}_2 + \text{CO}_2 \]  \hspace{1cm} (1)

Assuming 1 mol of CH4 is fed to the DFC® system; 4 mol of hydrogen will be produced. But, only 65% of the hydrogen (i.e. 2.6 mol) reacts at the anode and will result in the following equation.

Corresponding reaction at anode:

\[ 2.6\text{H}_2 + 2.6\text{CO}_2^2 \rightarrow 2.6\text{H}_2\text{O} + 2.6\text{CO}_2 + 2\text{e}^- \]  \hspace{1cm} (2)

The remaining 35% of the H2 (1.4 mol) and the entire CO2 (1 mol) from Equation (1) goes directly to the AOG. Combining the products from (2) and 1.4 mol of H2 and 1 mol of CO2 from (1) results in the following AOG composition.

\[ 1.4\text{H}_2 + 2.6\text{H}_2\text{O} + 3.6\text{CO}_2 \]  \hspace{1cm} (3)

But in reality, another internal reaction takes place in the DFC® fuel cell. One third of the H2 in Equation (3) (i.e. 0.47 mol) needs to be back-shifted to H2O and CO resulting in Equation (4).

\[ 0.47\text{H}_2 + 0.47\text{CO}_2 \rightarrow 0.47\text{H}_2\text{O} + 0.47\text{CO} \]  \hspace{1cm} (4)

Combining Equations (3) and (4) yields the following products:

\[ 0.93\text{H}_2 + 3.07\text{H}_2\text{O} + 0.47\text{CO} + 3.13\text{CO}_2 \]  \hspace{1cm} (5)

<table>
<thead>
<tr>
<th>Type of feedstock</th>
<th>Source</th>
<th>Collection</th>
<th>Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dog and cat food waste</td>
<td>Royal canin</td>
<td>Daily</td>
<td>Warehouse</td>
</tr>
<tr>
<td>Food waste</td>
<td>University courts</td>
<td>Daily</td>
<td>Food court</td>
</tr>
<tr>
<td>Wood chips</td>
<td>University power plant</td>
<td>Daily</td>
<td>Delivered at site</td>
</tr>
<tr>
<td>Waste water</td>
<td>SE Wastewater Treatment Plant</td>
<td>Daily</td>
<td>Delivered at site</td>
</tr>
<tr>
<td>MSW</td>
<td>Rolla municipal solid waste</td>
<td>Weekdays</td>
<td>Organic waste collection program</td>
</tr>
<tr>
<td>Brewery waste</td>
<td>Public House Brewery</td>
<td>Weekly</td>
<td>Organic waste collection program</td>
</tr>
<tr>
<td>Grape skin, rice hull and vines</td>
<td>St. James Winery</td>
<td>Seasonal</td>
<td>Winery/vineyard</td>
</tr>
<tr>
<td>Timber</td>
<td>MTNF</td>
<td>Seasonal</td>
<td>MTNF</td>
</tr>
</tbody>
</table>
Hence for every 1 mol of CH₄ the following AOG composition is obtained as on a molar percentage basis H₂O, CO₂, CO, and H₂ are 40.4, 41.2, 6.2, and 12.2 respectively with assuming 100% CH₄. The inlet fuel requirement of the DFC1500™ unit based on 37 MJ/m³ input fuel is calculated and found to be 286 m³/h consists of 198 mol of CH₄ and 4 mol of CO₂. The actual AOG flow rate of methane (mol/min) for H₂, H₂O, CO, and CO₂ is calculated using Equation (5) are 156.5, 516.8, 79.1 and 526.9 respectively.

3.3.2. Hydrogen recovery and cleaning system

In order to achieve a CHHP system, hydrogen from the AOG must be recovered, cleaned and distributed from the DFC™ fuel cell system. The details of the hydrogen recovery and purification process are shown in Fig. 2(b) [1–3].

The AOG outlet pressure is 1.08 bar and outlet temperature to be 600°C. The AOG is first cooled and pressurized to undergo water–gas shift reaction.

Water–gas shift reaction:

$$\text{H}_2\text{O} + \text{CO} \rightarrow \text{H}_2 + \text{CO}_2$$  \hspace{1cm} (6)

The entire CO present in the AOG reacts with H₂O to produce an additional 242 kg of H₂ and of $4 \times 10^3$ kg of CO₂ per day. The water vapor is condensed and recycled to the anode side of the fuel cell for the internal reforming of methane. The amount of water produced during condensation is greater than the fuel cell requirement with the excess water is sent into the sewer. The CO₂ and H₂ coming out of the water–gas shift reactor is cooled and separated using a PSA unit. The hydrogen coming out of the PSA unit is compressed and used for different applications on the university campus. Outside air is preheated using the heat exchanger and is mixed with the CO₂ coming out the PSA unit in AOG. The mixture is then transferred to the cathode to complete the cathode reaction as shown in Equation (7).

Reaction at cathode:

$$\text{CO}_2 + 0.5\text{O}_2 + 2\text{e}^- \rightarrow \text{CO}_3^2^-$$  \hspace{1cm} (7)

The flow rates of gases (mol/min) at HEX W.G. shift inlet for H₂, CO₂, H₂O, and CO are 156.5, 526.9, 516.8, and 79.1 while at HEX W.G. shift outlet 235.6, 606, 437.7 and 0.0 respectively. The amount of H₂
and CO₂ flow rate from PSA product outlet gas and tail gas are 212, 0.0, 23.6 and 606 respectively and of H₂ and N₂ at AGO inlet and cathode exhaust are 23.6, 23.6, 1140, and 1140 respectively. Moreover, the flow rates for CO₂ and O₂ at AGO inlet and cathode exhaust are 606, 181.8, 303 and 90.9 respectively. Theses flow rates are necessary to calculate the amount of hydrogen generated, amount of outside air needed, and amount of exhaust gas. The following assumptions were made during the calculations: (i) H₂ recovery rate from PSA unit is 90%; (ii) N₂ is inert and does not take part in the cathode reactions; (iii) amount of outside air was calculated based on the amount of CO₂ present on the PSA tail gas; (vi) only 70% of CO₂ undergoes reaction to maintain the CO₂ /CO₃ equilibrium inside the fuel cell. Based on the hydrogen flow rate from the PSA product outlet, the amount of hydrogen generated per day is approximately 650 kg [7,17].

3.4. Hydrogen compression, storage, dispensing/distribution system

The design will incorporate the system into the existing hydrogen infrastructure on the university campus. The existing hydrogen station was designed such that it could handle higher volume of hydrogen in the future. Currently, the hydrogen fueling station at the E3 Commons area has an electrolyzer capable of producing 4.2 kg of hydrogen per day, cascade storage tanks that can hold 33 kg of hydrogen at 450 bar, a hydrogen compressor capable of compressing 15 kg of hydrogen per day to 415 bar, and a 350 bar hydrogen dispenser. The product hydrogen from the PSA unit will be transferred into the buffer tank located in the adjacent hydrogen station via pipeline. The buffer tank feds two compressors; (i) the existing Hydro-Pac C06-10-70/140LX compressor (415 bar) and (ii) the PDC machines (PDC-13-1000-3000) compressor (250 bar). The compressed hydrogen from the Hydro-Pac compressor will be stored in existing storage tanks. Hydrogen from the PDC machine compressor will be used to fill a hydrogen tube trailer and K-cylinder manifold. The end use of hydrogen is discussed in the next section. The entire process of hydrogen compression, storage, dispensing and distribution is shown in Fig. 3(a) [1,2].

4. Results and discussion

4.1. Hydrogen End-Uses

The hydrogen usage (kg/day) on the university campus including personal transportation applications, backup power applications, portable power applications, and other mobility applications are 56, 16, 29, 17, and 5 respectively. The different applications, potential users, and total hydrogen usage per day (123 kg/day) are shown in Fig. 3(b).
The major use of the hydrogen on the university campus is for fueling personal transporters. They include fuel cell scooters, Segways and electric bikes retrofitted with fuel cells. The Segways and electric bikes will be retrofitted in-house at the hydrogen research and development garage. The retrofitted Segways and bikes will have fuel cells that act as range extenders for the on-board batteries and will recharge it when the state of charge falls below a certain set value. The design also incorporates different hydrogen mobility applications for the university campus.

Providing reliable and high quality power to the IT department is vital. Therefore, the design includes a fuel cell UPS unit in the design. It consists of three 8 kW PEM fuel cells and is designed specifically for larger communications backup power loads within the wireless and wireline telecommunications. These units are outdoor units and have a cabinet to accommodate the hydrogen storage cylinders.

Another innovative idea used is the blending of hydrogen with diesel while running backup diesel generators. Blending small percentage of hydrogen with diesel fuel has shown to reduce the total fuel consumption of the generator and reduced emissions.

5. Conclusion

In this paper, we have discussed the Hydrogen production, recovery, cleaning, and End-Uses on the university campus from CHHP system by using local resources. Following the resource assessment study, the team selects FuelCell Energy DFC1500™ unit for its fuel cell. The CHHP system provides hydrogen for transportation, backup power and other needs. In conclusion, The CHHP system will be able to provide 650 kg of hydrogen to the university campus per day and reduce energy consumption, fossil fuel usage and GHG emissions at the Missouri S&T campus.
Acknowledgments

The authors wish to acknowledge the Hydrogen Education Foundation for their support of the annual Hydrogen Student Design Contest which challenges university students to design hydrogen energy applications for real-world use.

Appendix A. Supplemental data

The full report submission for the Hydrogen Education Foundation’s Hydrogen Student Design Contest is available online: http://hydrogencontest.org/previous.asp.

References