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Investigating the Use of Combined Hydrogen, Heat and Power System for Omar AL-Mukhtar University Campus

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This paper investigates the use of a combined hydrogen, heat, and power (CHHP) system for Omar Al-Mukhtar university campus using local resources. Based on previous local resource assessment studies, the hydrogen team of Omar AL-Mukhtar University (OMU) selected the fuelcell energy DFC4000^{TM} unit. This study shows that the CHHP system can provide electricity to power the university campus, thermal energy for heating the anaerobic digester, and hydrogen for transportation, back-up power and other needs. Consequently, using the alternative fuels and renewable energy resources for OMU campus can lower fossil fuel consumption and, therefore, greenhouse gas emissions (GHG).

Keywords: Hydrogen; combined hydrogen, heat, and power; anaerobic digestion; pressure swing adsorption; renewable energy

549. **INTRODUCTION**

OMU campus in El-Beida city is the fourth largest campus in Libya with 1.9 km^2 and approximately 7000 students. The university is one of El-Beida's largest electric power consumers with a peak demand of 13.78 Mwe and annual electric energy consumption of 5.53 × 10^6 kWh/yr. Currently, electrical power of the university campus is purchased from General Electricity Company of Libya (GECOL) and distributed from the substation and switchgear located at the campus power plant. Biogas produced by anaerobic digestion of wastewater, organic waste, agricultural waste, animal 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 (MCFC). The power generated by the CHHP system is used at various locations on the campus to reduce the total electric power purchased and minimize air pollution to benefit overall community health [1–4]. Therefore, the CHHP system has higher efficiency than other distributed generation plants of similar size [5, 6]. The hydrogen generated is used to power different applications on the university campus, including personal transportation, backing power, portable power, and mobility/utility applications. Local available feed stocks near OMU university campus that can be used for biogas production were identified [7–9]. An energy flow and resource availability study was performed to identify the type and source of feedstock required to continuously run the CHHP system to produce maximum capacity of electricity, heat recovery and hydrogen [10].

Nomenclatures	
OMU	Omar AL-Mukhtar University
CHHP	Combined heat, hydrogen and power system
GHG	Greenhouse gas
MCFC	Molten carbonate fuelcell
DFC	Direct fuel cell
MSW	Municipal solid waste
AD	Anaerobic digestion
PSA	Pressure swing adsorption
AOG	Anode outlet gas
HEX.W.G	Heat exchanger water and gas
AGO	Anode gas oxidizer
CHP	Combined heat and power
VS	Volatile solids

2.0 EXPERIMENTAL PROCEDURE

2.1. Location

Hydrogen team of OMU selected the location of the CHHP plant at OMU campus to be in the southwest side as shown in Figure1. Due to the size of the system, the space needed should be sufficiently large as well. This location also satisfies safety and nuisance requirements due to the complication arising from storage of waste and hydrogen. The site also has the advantage of being near large enough road to allow for easy access by the campus's shuttle system. Furthermore, visibility of the CHHP plant in the campus will encourage promotion of clean waste-to-energy, hydrogen, and sustainability concepts of students and staff.

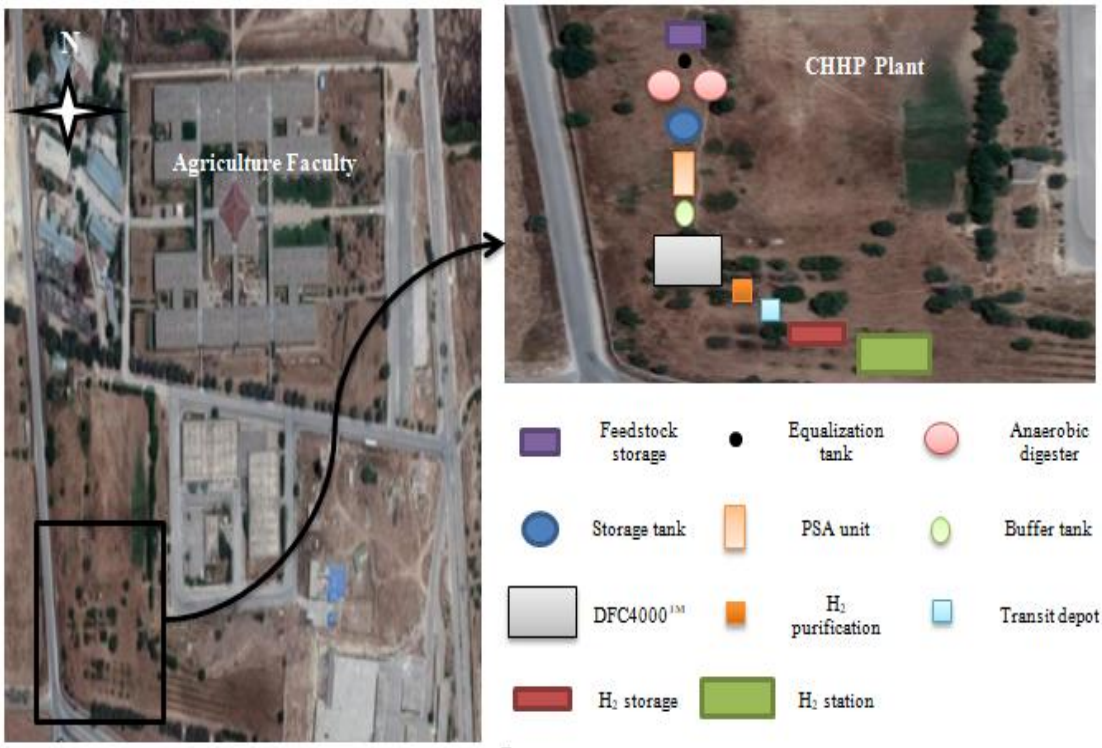

Figure1: Location with anaerobic digester, CHHP plant, and hydrogen fueling station.

2.2. CHHP system technical design

This section describes the design of the major components and explains the various processes occurring during system operation. The design discussed in this paper has three major systems: (i) anaerobic digestion system, (ii) CHHP system consisting of a DFC4000^{TM} fuelcell unit, and (iii) Hydrogen recovery, cleaning, compression, storage, dispensing, and distribution system on university campus from CHHP system [3, 10]. These systems were designed based on the results from the feedstock assessment and the expected biogas production from local resources. It was found that the anticipated methane production after biogas treatment is 651.1 m^3/h with a heat content of 159.66 MJ/m^3. Consequently, a DFC4000^{TM} unit was selected for the CHHP system for which local resources can provide 100% of the fuel requirements. DFC4000^{TM} completely operates by biogas and does not need purchased natural gas from the local utility company.

The anaerobic digestion system and the CHHP system are sized based on the amount of locally available feedstock and the amount of methane gas generated respectively [13, 14]. The hydrogen recovery, purification, compression, storage, and distribution system are designed based on the hydrogen demand on the university campus and the 65% fuel utilization rate [3, 15]. The following section describes the major components of the system.

2.3. Feedstock delivery system and pretreatment tank

Feedstock is collected and transported to the storage facility. The storage facility consists of a 48.22 m ×48.22 m (2325 m^2) steel building to protect the feedstock from the elements [16]. It houses a macerator to chop feedstock larger in diameter than 0.05 m to aid in the methane production rate in the digester. The design employs a 38 kWeTaskmaster® 1600 shedder from Franklin Miller Incto that reduces the size of the feedstock [17, 18]. The processed feedstock will be stored in a cement storage bin in the storage facility.

2.4. Anaerobic digestion system

Digesters and biogas production are shown in Figure2 [13]. The feedstock from the cement storage bin is transported via a screw feeder to a hygienestation unit where it is heated to 70 °C for one hour to remove all the pathogens [19, 20]. After heating, the feedstock is transported to a 113.5 m^3 equalization tank where the biomass is mixed to form a homogenous mixture before being fed into the digester. The digester used in the design is a complete-mix anaerobic digester from Siemens Company and is a concrete tank with a diameter of 38.125 m and a tank side water depth of 16 m. The tank wall height below grade is 18.25 m and has a floor slope of 1:6. The outer wall is insulated and the inner wall of the tank is lined with stainless steel hot water pipes to maintain an optimum temperature of 40°C.

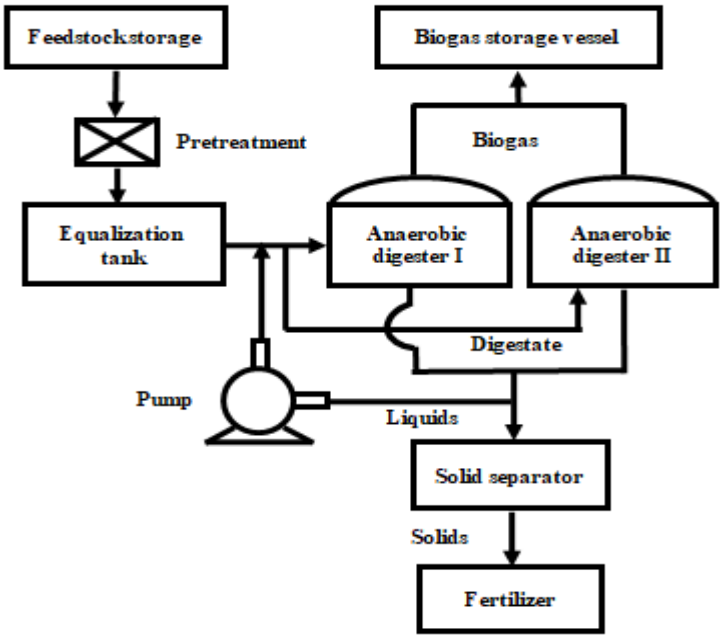

Figure 2: Flow diagram for digester and biogas production.

The design uses a highly efficient Jet Mix™ Vortex Mixing System by Siemens, to mix the biomass inside the digester. The system suspends organic and inorganic solids with intermittent mixing, making possible power savings of up to 50% or more. The system maintains efficiency regardless of tank level and minimizes dead spots due to its innovative mixing pattern and also has the capability to mix multiple tanks using one central pumping facility. This system will eliminate the use of multiple pumps and will reduce the capital cost of the digester system. The proposed anaerobic digester is sized such that it has retention time of 21 days. The specification and details of the digester are shown in **Table** 1 [21, 22].

Table 1: Digester data.	
Tank side water depth	16 m
Tank wall height (below grade)	18.25 m
Tank diameter	38.125 m
Cone per tank	1115 m^3
Tank wall thickness	0.30 m
Floor slope	1:6
Quantity of solids to digester	36×10^3kg/day
Retention time	21 days
Volatile solids concentration	80%
Anticipated solids reduction	50%
Anticipated gas yield	0.93 m^3/kg VS[a] destroyed
Anticipated biogas production	550 m^3/h
Anticipated natural gas equivalent	330 m^3/h
[a] Volatile solids	

Inside the anaerobic digester, microorganisms act on the organic feedstock to produce biogas; digest ate, and water [10]. The anticipated biogas production from the digester is 1100 m3/h or 660 m3/h of natural gas equivalent (assuming biogas concentration is 60% methane and 40% carbon dioxide)[1, 23].

2.5. **Gas treatment system and fuel storage**

Two main adsorption technologies are being considered: pressure swing adsorption (PSA) and temperature swing adsorption (TSA). The mean difference between the PSA and TSA methods refers to the strategy for regenerating the adsorbent after the adsorption step and the time duration of an individual adsorption circle and adsorption circle in varied temperature technology generally takes several times longer than in varied-pressure technology. On other hand, in PSA applications, the pressure of the bed is reduced, whereas in TSA, the temperature is raised while pressure is maintained approximately constant. In this project, the step time for desorption is of the same order of magnitude as that of the adsorption (sometimes even smaller). Consequently, this process enjoys shorter cycle time and better efficiency also by using Zeolites 13X compared to TSA, and accordingly, is chosen. In addition, the most of studies dealing with CO_2 capture use Zeolites 13X as adsorbent in PSA or TSA technologies because Zeolite 13X has high selectivity to CO_2.

Biogas from the anaerobic digestion is stored in a buffer tank which supplies biogas to the gas treatment system. The treatment system uses PSA technology to separate methane present in the biogas [24, 25]. The design has a total of eight absorbers to ensure a continuous stream of high quality methane. While carbon dioxide (CO_2), hydrogen sulfide (H_2S) and other impurities in one set of tanks are desorbing, biogas will be fed to the second set of tanks for adsorption. The product from this gas treatment system is pipe line quality natural gas which is fed into the fuel cell [26, 27]. Even though the DFC® fuelcell units can handle 60% methane and 40% carbon dioxide without affecting its efficiency, the design included the PSA unit for the following reasons [1]:

i. The DFC® units cannot accept H_2S, water (H_2O), and other impurities in its input fuel. Therefore, biogas treatment is necessary before feeding it into the fuel cell under all conditions [1, 28].

ii. Inlet fuel pressure to the fuelcell should be between 2 – 2.4 bar. If the fuel contains 40% carbon dioxide, it will impact the sizing and the equipment downstream the fuel cell of the design will require a higher capacity heat exchanger, water-gas shift reactor, and hydrogen purification or separation system. The DFC4000™ requires 651.1m^3/h of natural gas at 34.65MJ/m^3. If biogas (60% methane and 40% carbon dioxide) is utilized, the fuelcell system will require 477m^3/h of biogas as fuel to operate. This will increase the size of the equipment downstream the fuelcell by 55% and will increase its capital cost which is not desirable [1, 29].

iii. The product gas from the PSA unit is expected to have an average heat content of 34.65MJ/m^3 which is roughly equal to the average heat content of natural gas consumed in OMU (34.65MJ/m^3). Hence, the fuelcell unit will receive a consistent fuel throughout its operation. The process and flow during the biogas treatment is illustrated in Figure 3.

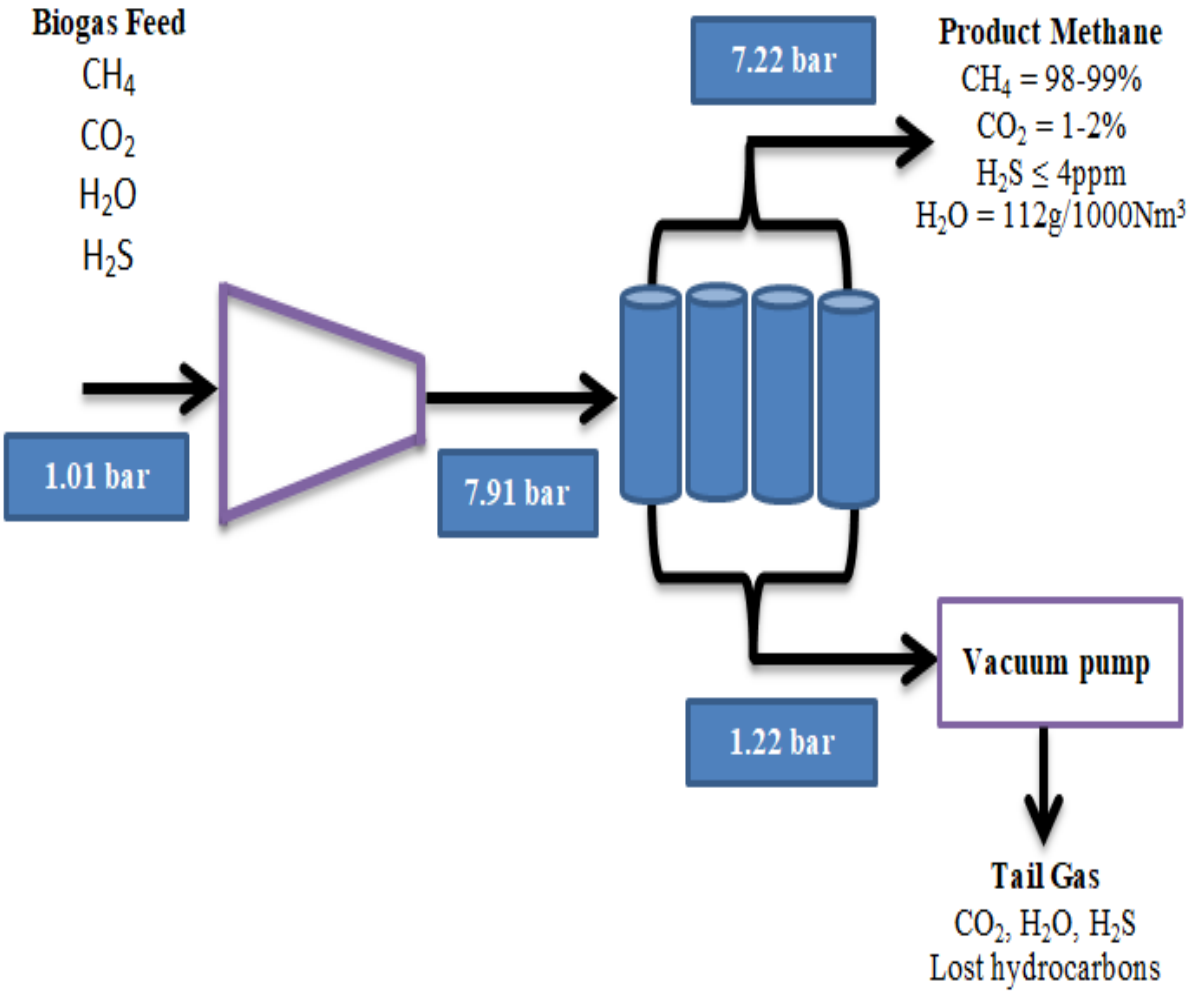

Figure 3: The process and flow during the biogas treatment.

3. DFC4000^{TM} Fuel Cell power plant

The two anaerobic digesters system will be able to supply 100% of fuel for the DFC4000^{TM} unit from locally available feedstock. Figure 4 shows the reactions taking place inside the fuelcell [1, 14].

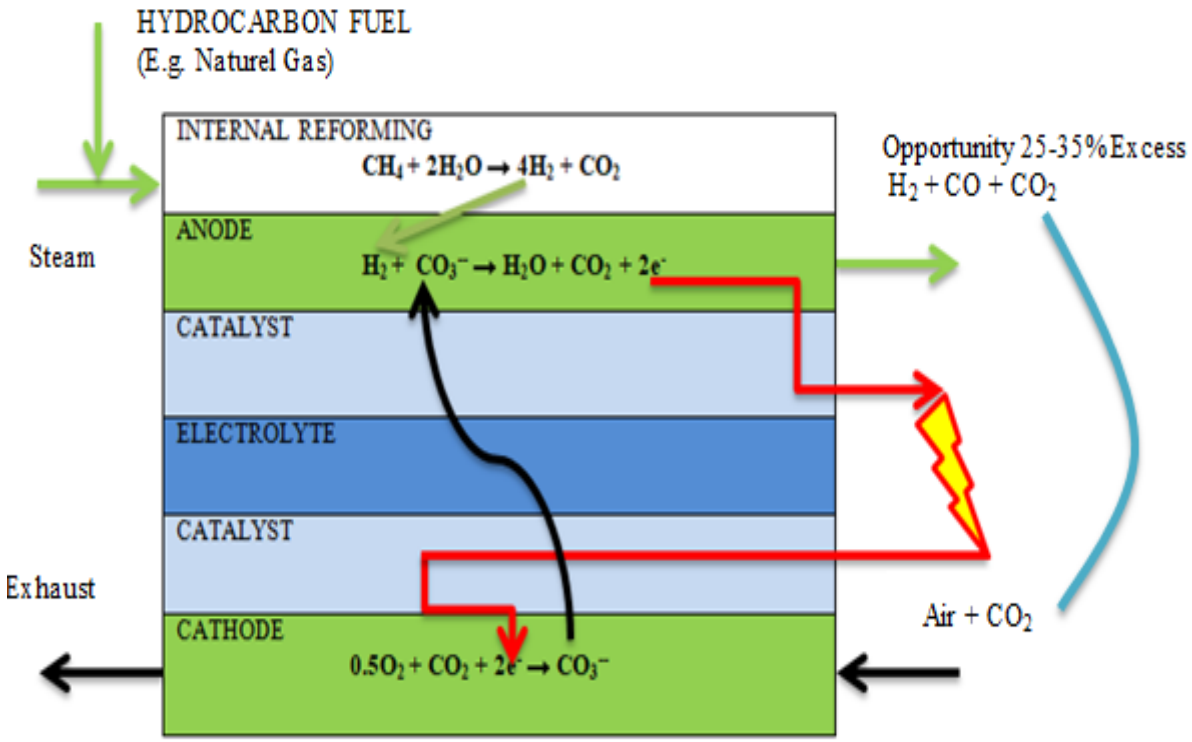

Figure 4: Internal reforming DFC® technology.

3.1. **Anode Outlet Gas (AOG) calculations**

The AOG calculations are remade based on the AOG composition calculation document provided by fuelcell energy [23, 30]. 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 H_2 produced is reacted at the anode to produce electricity. In order to reflect the AOG composition, it is assumed that one third of the 35% hydrogen produced is back-shifted to produce H_2O and CO. Based on these assumptions and the processes taking place inside the fuelcell, the following equations (1 – 5) for every one mole of methane (CH_4) entering the anode side are obtained.

Internal reforming:

$CH_4 + 2\,H_2O \rightarrow 4\,H_2 + CO_2$ ……(1)

Assuming one mole of CH_4 is fed to the DFC® system; only 65% of the hydrogen (i.e. 2.6 moles) reacts at the anode and will result in the following equation.

Corresponding reaction at anode:

$2.6\,H_2 + 2.6\,CO_3^{--} \rightarrow 2.6\,H_2O + 2.6\,CO_2 + 2\,e^-$ ……(2)

The remaining 35% of the H_2 (1.4 moles) and the entire CO_2 (1 mole) from equation (1) goes directly to the AOG. Combining the products from (2) and 1.4 moles of H_2 and 1 mole of CO_2 from (1) results in the following AOG composition.

$1.4\,H_2 + 2.6H_2O + 3.6\,CO_2$ ……(3)

But in reality, another internal reaction takes place in the DFC® fuel cell. One third of the H_2 in equation (3) (i.e. 0.47 moles) needs to back-shifted to H_2O and CO resulting in equation (4).

$0.47H_2 + 0.47\ CO_2 \rightarrow 0.47\ H_2O + 0.47\ CO$ ..... (4)

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

$0.93\ H_2 + 3.07\ H_2O + 0.47\ CO + 3.13\ CO_2$ .....(5)

The inlet fuel requirement of the DFC4000™ unit based on 156 MJ/m^3 input fuel is calculated and found to be 651.1 m^3/h. Assuming that the input fuel consists of 98% CH_4 and 2% CO_2, 651.1 m^3/h of fuel consists of 451 moles of CH_4 and 9 moles of CO_2. The actual AOG flow rate corresponding to 451 moles of methane per minute is calculated using equation (5).

3.2. **Hydrogen Recovery and Purification System**

In order to succeed a CHHP system, hydrogen from the AOG must be recovered, cleaned and distributed from the DFC® fuelcell system. This section explains the hydrogen recovery and water-gas shift reaction for additional hydrogen production, removal and recycling of water, purification of hydrogen gas, and CO_2 transfer to the cathode side of the fuelcell [31]. The details of the hydrogen recovery and purification process are shown in Figure 5.

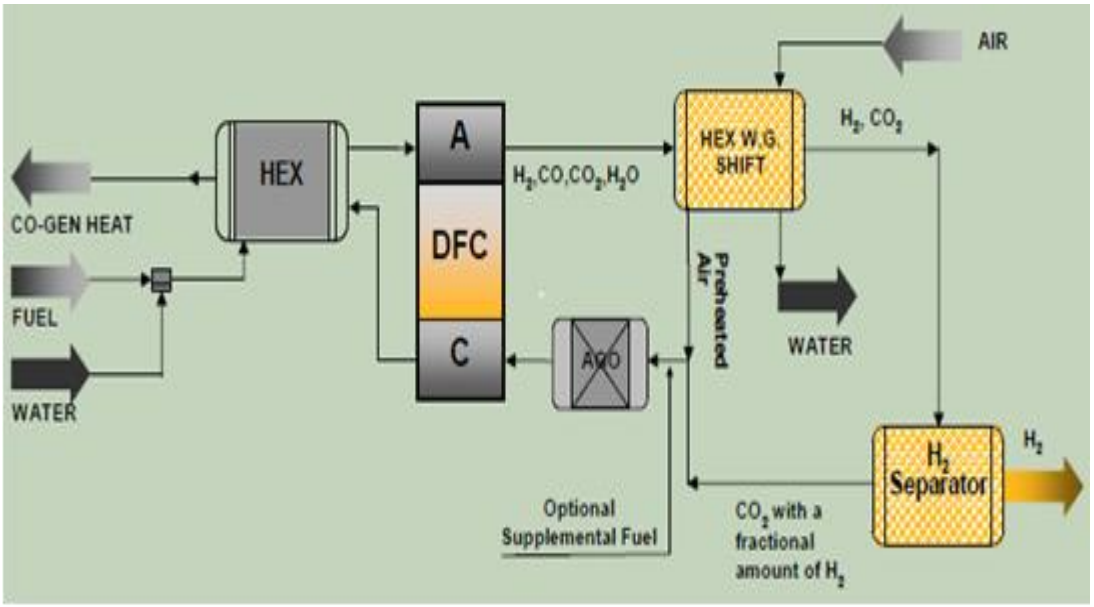

Figure 5: Hydrogen recovery and purification.

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:

$H_2O + CO \rightarrow H_2 + CO_2$ .....(6)

The entire CO present in the AOG reacts with H_2O to produce an additional 242 kg of H_2 and of 4×10^3kg of CO_2 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 fuelcell requirement with the excess water is sent into the sewer. The CO_2 and H_2 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 CO_2 coming out the PSA unit in Anode Gas Oxidizer (AGO). The mixture is then transferred to the cathode to complete the cathode reaction as shown in equation (7).

Reaction at cathode:

$CO_2 + 0.5\ O_2 + 2\ e^- \rightarrow CO_3$ .....(7)

The flow rates of gases at different stages were estimated and tabulated in Table 2. 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) H_2 recovery rate from PSA unit is 90%; (ii) air consist of 79% N_2 and 21% O_2; (iii) N_2 is inert and does not take part in the cathode reactions; (iv) amount of outside air was calculated based on the amount of CO_2 present on the PSA tail gas; (v) only 70% of CO_2 undergoes reaction to maintain the CO_3^{--} equilibrium inside the fuelcell. Based on the hydrogen flow rate from the PSA product outlet, the amount of hydrogen generated per day is approximately 1480 kg.

Table 2: Flow of gases at different sections of the system.

Gas	HEX W.G. shift inlet (mol/min)	HEX W.G. shift outlet (mol/min)	PSA product outlet (mol/min)	PSA tail gas (mol/min)	AGO inlet (mol/min)	cathode exhaust (mol/min)
H_2	356.5	536.6	483	53.6	53.6	53.8
CO_2	1200.2	1380.3	-	1380.3	1380.3	414.1
H_2O	1177.2	997.2	-	-	-	-
CO	180.2	-	-	-	-	-
O_2	-	-	-	-	690.15	207.05
N_2	-	-	-	-	2,597	2,597

3.3. **Hydrogen compression, storage, dispensing /distribution system**

The system will be incorporated 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. 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.

4. RESULTS AND DISCUSSION

4.1. **Application energy end-uses on the university campus from CHHP system.**

This section explains how to use the output from the DFC4000^{TM} fuelcell (Heat, Hydrogen, and Electricity on the campus). Fuelcells operating on methane from biogas offer a pathway to renewable electricity generation Tri-generation of electricity, heat, and hydrogen offers an alternative route to solving the H_2 infrastructure problem facing fuelcell vehicle deployment. Consequently, it will be promoting biogas fuelcells in the future under its market transformation programs. Finally, this part gives details for calculation electric, heat recovery, and hydrogen output from the CHHP system.

4.2. **Electricity use**

The electric power output of the DFC4000^{TM} unit operating in the simple cycle CHP mode is 3.7 MWe. This corresponds to the net power after providing the parasitic loads for its Mechanical Balance of the Plant (MBOP) and energy loss in the Electrical Balance of the Plant (E-BOP). However, there are additional components that require electric power for the DFC4000^{TM} unit operating in CHHP mode. These components, including the heat exchanger for AOG cooling, the water-gas shift reactor, and the PSA unit for hydrogen purification and operate collectively with the fuelcell unit to form the CHHP system. Based on the power requirements of these components, the net power output

from the CHHP system was estimated to be 3.2 MWe. The total electric power requirement of different equipment used in the design is estimated to be approximately 474 kWe and is tabulated in Table 3.

Table 3: Power demand and energy consumption.

Equipment	Max. power rating (kW_e)	Daily operation time (h)	Daily energy consumption (kWh)
Feedstock storage facility	7	12	84
Macerator	38	4	152
Screw feeder	7	4	28
Pump	100	4	400
Hygienization unit	9	4	36
Anaerobic digester	8	24	192
Storage tank	7	24	168
Biogas PSA unit	95	24	2.28×10^3
Hydrogen compressor Comp1	12.5	24	300
Hydrogen compressor Comp2	165	24	3.96×10^3
Auxiliary loads	25	16	400
Total	473.5	164	8,000

Auxiliary loads include site lighting, safety devices, hydrogen dispenser, and electric loads at central control station. The total net energy production from the CHHP system is 76.8×10^3 kWh per day and the energy demand for on-site use is 8,000 kWh per day. Hence, the CHHP system will be able to provide 68.8×10^3 kWh per day to the university campus. This corresponds to 23% of the whole campus electricity requirement.

4.3. **The heat recovery system use**

The DFC4000^{TM} unit has 4GJ/h at 49°C available for heat recovery while operating in CHP mode. However, the recoverable heat from a DFC4000^{TM} unit operating in CHHP mode is considerably lower than compared to the operating in CHP mode. This is due to the cooling of anode outlet gas, removal of water vapor, hydrogen recovery, and lower flow rate of the exhaust gases. The thermal energy available for heat recovery was calculated based on the cathode exhaust gas composition and equation (8) is shown in Table 4. The temperature difference of the input and output temperature of the heat recovery system is approximately 322 °C.

$$Q = m \times C_P (\Delta T) \quad (8)$$

Where m, CP and ΔT are the mass flow rate of the gas(kg/h), the specific heat of the gas (kJ/kg.K) and the change in temperature of the gas (K) respectively.

Table 4: Thermal energy available for heat recovery from the DFC4000^{TM} CHHP system.

Gas	Cathode exhaust (kmol/min)	Mass flow rate (kg/h)	Cp (kJ/kg.K)	ΔT (K)	Q flow rate (MJ/h)
H_2	0.054	6.41	14.32	322	29.6
CO_2	0.414	451.95	0.84	322	122.2
O_2	0.207	347.56	0.92	322	103
N_2	2.597	4,985.1	1.04	322	1,669.4
Total		5,791.02			1,924.2

The low thermal energy from the DFC4000^{TM} unit can be attributed to the low flow rate of the exhaust gases when compared to the DFC4000^{TM} in CHP cycle. Two components in the system that require heat energy are (i) hygienization unit and (ii) anaerobic digester. Hygienization of feedstock prevents pathogens from entering the digester and maintaining optimum temperature inside the anaerobic digester ensures maximum biogas production. The mass of the feedstock and digester sludge that need to be heated are 36×10^{3}kg/day and 12×10^{6}kg/day, respectively. The temperature of feedstock was assumed to be 20°C. The digester is heated to 40°C during its initial fill and is assumed to lose 1°C on average every hour due to environmental losses. Table5 shows that the total load for these two systems is greater than the recoverable heat. Therefore, additional thermal load requirement will be met using an external natural gas heater.

Table 5: Thermal load of the system.

Thermal load	Mass flow rate (kg/h)	Cp (kJ/kg.K)	ΔT (K)	Q flow rate (MJ/h)
Hygienization unit	1,500	2.3	50	172.5
Anaerobic digester	500,000	4.2	1	2,100
Total				2,272.5

5. CONCLUSION

In this paper an attempt is studied the design of a CHHP system for OMU campus using local resources. The study shows that the CHHP system can provide electricity to power the university campus, thermal energy for heating the anaerobic digester, and hydrogen for transportation, back-up power and other needs. The CHHP system will be able to provide approximately 68,800 kWh and 1480 kg/day of hydrogen to the university campus. Ultimately, the CHHP system will reduce energy consumption, fossil fuel usage, and GHG. It will be able to provide approximately 23% of the university campus's electricity need.

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