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Combined Heat, Hydrogen and Power Production from Seaweed Biogas-Fuelled Solid Oxide Fuel Cell (Sofc) System

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In this work, 3 MW solid oxide fuel cell (SOFC) system fuelled by seaweed biogas was integrated into polygeneration process: combined heat, hydrogen, and power (CHHP) and its feasibility was evaluated. The integrated process was rigorously simulated using Aspen Plus and techno-economic analysis was performed to evaluate the feasibility of the proposed processes using the target cost of $225/kW as the initial SOFC stack price and the current and projected lifetimes of SOFC. Comprehensive sensitivity analyses were also performed on economic parameters to assess uncertainties in the process. Results show that the integrated CHHP process can generate 2.3 MW of net power and 50 kg/hr of hydrogen from 2,000 kg/hr of seaweed biogas with efficiency of 47%. The calculated levelized electricity cost was 10.45 ¢/kWh, which is comparable to existing fixed power generation.

1. Introduction

From 2015 to 2040, global energy consumption is expected to increase by 28%, of which nearly 80% will be supplied by fossil fuels (US EIA, 2019). However, as fossil fuels are increasingly depleted and environmental problems increase, renewable fuels become essential. Biofuels from macroalgae, one of the third generation biomass, are one solution to this problem. macroalgae, i.e., seaweeds, do not require land for cultivation and are more productive per unit area than land crops. Brown algae (e.g. kelp) are the most common of these.

Anaerobic digestion, which produces biogas, is one of the oldest biochemical conversion pathways among biomass conversion pathways, and the technology has been used since ancient times. This anaerobic digestion produces biomethane from biomass, which can produce up to 20,800 m^3/ha/yr of biomethane when kelp (*Saccharina japonica*) is used as a raw material. This is very high when compared to other macroalgae as well as first generation biomass such as corn (Murphy et al., 2015). Fasahati et al. (2017) designed and simulated the industrial-scale anaerobic digestion process of kelp producing biogas. The gases produced in these processes mainly include methane (CH_4), carbon dioxide (CO_2), hydrogen (H_2) and water (H_2O) and can be used as fuel for power generation systems such as turbine generators as well as fuel cells.

Compared with other conventional stationary power generation, fuel cells can convert chemical energy directly into electrical energy without combustion and also produce heat and hydrogen simultaneously (US NREL, 2013). Fuel cells not only provide higher electrical efficiency than combustion-based generators, but also generate less hydrocarbon pollutants (Ormerod, 2003). Solid oxide fuel cells (SOFCs) operate at the highest temperatures (approximately 750-1,000 °C), and this excess heat is utilized in combined heat and power (CHP) process. Natural gas is generally used as fuel for SOFCs, but it is possible to use biogas or other renewable fuels as a substitute. Thus, SOFCs using biogas as fuel enable true green development (Dietrich et al., 2011).

Currently, the US National Institute of Energy Research (NETL) aims to reduce the cost of SOFCs and increase safety as well as performance (Kim et al., 2017). Commercial success in SOFCs requires at least five years or about 40,000 hours of life. According to US NETL (US NETL, 2011), SOFCs have a performance degradation of about 1% per 1,000 hours, with a lifespan of about two years as of 2011. But recently, according to NETL, SOFC has already reached 25,000 hours of life (US DoE, 2017). The rate of decline is

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expected to decrease by 0.5–1.0% per 1,000 hours in 2020 and 0.2% per 1,000 hours in 2025, with power generation system prices targeting $6,000/kW in 2020 and $900/kW in 2025 (Vora, 2016).

Many works have been done on the design and analysis of CHP processes at various scales and sizes, combining SOFCs with gas turbines (GTs), steam turbines (STs), or organic ranking cycles (ORCs) (Arsalis, 2008; Eveloy et al., 2016). However, most of these studies use natural gas as a fuel that does not require gas cleaning, and economic analysis does not take into account the lifetime of the SOFC, nor does it take into account the expected future stack price decline. Furthermore, research on CHHP based on SOFCs fueled by biogas is even scarcer.

This study will focus on the design, optimization, and techno-economic analysis of modern CHHP processes that combine SOFCs fueled by seaweed biogas and organic ranking cycles (ORCs). The study will also analyze and predict SOFC performance for a realistic techno-economic scenarios considering current and future SOFC technology development.

2. Process and techno-economic modelling

2.1 SOFC

The modified SOFC model is based on the Siemens-Westinghouse tubular SOFC (Zhang et al., 2017). To power it, seaweed biogas after cleanup used as fuel instead of natural gas (Table 1). In this process, only one 3 MW SOFC using 2,000 kg/hr of seaweed biogas is simulated. The main difference between the CHP process and CHHP is the after-burner. In CHHP the after-burner is removed because the anode exhaust represents the feed for the next process or the hydrogen production (Li et al., 2013). Without the after-burner, the less heat can be recovered from SOFC in CHHP compared to the CHP process. Both the anode and cathode exhausts are used to pre-heat biogas and air. Anode exhaust is then flowed to the hydrogen production segment, while the cathode exhaust is flowed to the ORC. Anode exhaust components are summarized in Table 2.

Table 1: Biogas composition before and after cleanup

Component	Mole (%)	
	before cleanup	after cleanup
CH_4	27.50	49.54
CO_2	38.20	1.12
H_2	26.30	44.89
H_2O	5.30	0.31
N_2	0.15	0.28
O_2	2.08	3.86
NH_3	0.10	1 ppm
H_2S	0.46	1 ppm

Table 2: Components at anode exhaust

Components	Mole (%)
CO	8.9
H_2	21.3
CO_2	18.0
H_2O	52.6
N_2	0.1
H_2S	0.7 ppm

2.2 Hydrogen production

Hydrogen production process is adapted from a pilot MCFC-CHHP plant (Li et al., 2013). First, the anode exhaust is compressed to 15 atm with a compression ratio of 3.8. It is subsequently cooled down to 400°C before entering the WGS (water gas shift) reactor where 90% of CO is converted to H_2. Since this reaction is endothermic, the outlet temperature is de-creased to 350°C. WGS reactor exhaust is then cooled down to 73°C and 97% of water is removed from the stream, purifying the H_2 to 50%. H_2 is purified further using pressure swing adsorption (PSA), resulting in 50 kg/hr of 99.99% pure H_2. Part of the PSA output must be recycled to the PSA input so that its H_2 input will be kept higher than 75% at all times. This must be done to make sure that the PSA process is feasible.

2.3 ORC (organic Rankine cycle)

Cathode exhaust which has been used to pre-heat the air feed still contains heat. Using ORC as the bottom cycle, this waste heat is recovered. The ORC model follows the NREL (National Renewable Energy Laboratory) model with a recuperated cascade (US NREL, 2006). Basically, the working fluid is compressed using a pump to 30 atm, and then heated and vaporized using the cathode exhaust. The fluid is then expanded using a turbine where energy is obtained. The expansion results in a mix of vapour and liquid of the working fluid. The mixed fluid is fully condensed and re-pumped. This cycle is repeated, and 2% per year of working fluid is assumed to be lost into the atmosphere due to piping imperfection. Efficiency of the system can be increased by recuperating the hotter fluid from the turbine outlet and the cold liquid from the pump outlet.

2.4 Techno-economic modelling

Techno-economic model used in this work to analyze the process is based on the one developed by US NREL (US NREL, 2011). This model uses "nth-plant" economics, where the economic analysis is based on another built and operated plant which has employs the same technology.

Purchased equipment costs of compressors, blowers, pump, and heat exchangers are calculated based on Turton et al. (2012), GT price using the equation by Arsalis (2008), while the ORC price was calculated using the equation by Ghirardo et al. (2011).

3. Simulation and analysis results

Process flow diagram of the proposed process is shown in Figure 1. Since this process does not require much utilities, cooling water system is not included and it is assumed that water is obtained from outside of battery limit.

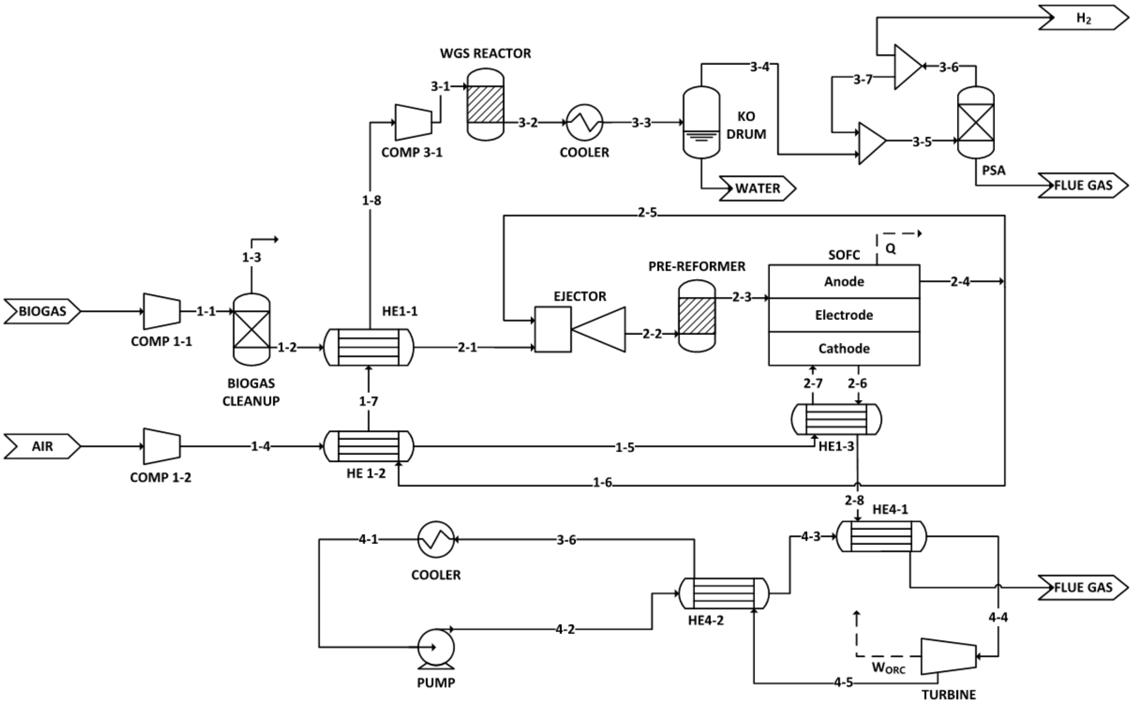

Figure 1: Process diagram of the proposed CHHP system

3.1 Simulation

Simulation conditions and results using Aspen Plus for the CHHP process are summarized in Table 3. As mentioned earlier, the SOFC simulation in this CHHP process is similar to the CHP process, only without an after-burner. And therefore, there is less available heat for pre-heating the air and biogas. In turn, this affects the process and the efficiency of the SOFC, making it lower compared to the CHP process. This also lowers the voltage value.

Overall electrical efficiency also becomes lower because a part of the produced electricity is used to power compressors within the H_2 production segment as detailed in Table 4. Though the efficiency is lower, this process produces hydrogen along heat and electricity, and this greatly affects the profitability of the process.

Table 3: Simulation conditions and results of the CHHP process

Biogas flow	2,000kg/hr
Pre-reformer methane conversion	37%
T_{SOFC}	850°C
U_a	25%
U_f	75%
Net Power	2.3 MW
Voltage	0.7 V
SOFC Efficiency (LHV)	47%
Overall Efficiency (LHV)	37%
H_2 production	50 kg/hr

Table 4: Plant electricity breakdown

Segments	Unit	Power/kW
Feed pre-treatment	Fuel compressor	-122
	Air compressor	-277
SOFC		3000
ORC	Blower	-52
	Turbine	266
	Pump	-17
Hydrogen production	Compressor 1	-210
	Compressor 2	-247
Net Power		2,342

3.2 Techno-economic analysis

Currently SOFC stack has relatively short lifetime, so it must be replaced every few years. Plant life of 20 years was used as the base case to decide how many stack replacements are needed in each of the scenarios. The stack replacement cost is variable, and varies with the power output value (US NETL, 2014). Assuming that commercial fuel cell will start with a stack price of $225/kW (US NETL, 2013), the scenario assumes that SOFC stack will have lower degradation rate and a longer lifetime as time progresses. Therefore, it is assumed that the initial stack lasts for 5 years, first replacement stack for another 6.5 years, whereas the second replacement lasts for 8.5 years in this scenario.

The BESP (break-even electricity selling price) was calculated to be 10.45 ¢/kWh and Table 5 summarizes the plant cost worksheet of CHHP process in detail.

The biogas price was assumed to be $0.125/kg (10% profit). and in Figure 2, it is shown that biogas price contributes the most to the BESP followed by SOFC capital. This high cost of biogas is balanced with the H_2 price which is assumed to be $5/kg.

Impact of economic parameters on the BESP of the CHHP process are shown in Figure 3. The stack cost is varied by 50% and 100%, and this corresponds to an increase of BESP to 11.61 ¢/kWh and 12.77, respectively. The hydrogen price is varied to $4.2/kg and $6.5/kg28, changing the BESP to 12.16 ¢/kWh and 7.25 ¢/kWh, respectively. Varying the FCI by 25% change the BESP to 8.98 ¢/kWh and 11.91 ¢/kWh. Lastly, increasing the IRR to 15% and 20%, increase the BESP to 12.69 and 15.25 ¢/kWh. From the graph a change of the H_2 price and IRR had the highest impact to BESP.

Table 5: Total capital investment (TCI), total variable and fixed operating cost for the CHHP (in 2016$)

	Present Value / million $
Total Installed Costs (TIC)	3.8
Total Direct Costs (TDC)	4.4
Total Indirect Costs	2.7
Fixed Capital Investment (FCI)	2.7
Land	0.2
Working Capital	0.4
Total Capital Investment (TCI)	7.7
Total variable operating cost (per year)	3
Total fixed operating cost (per year)	3
Overall Efficiency (LHV)	0.22
H_2 production	

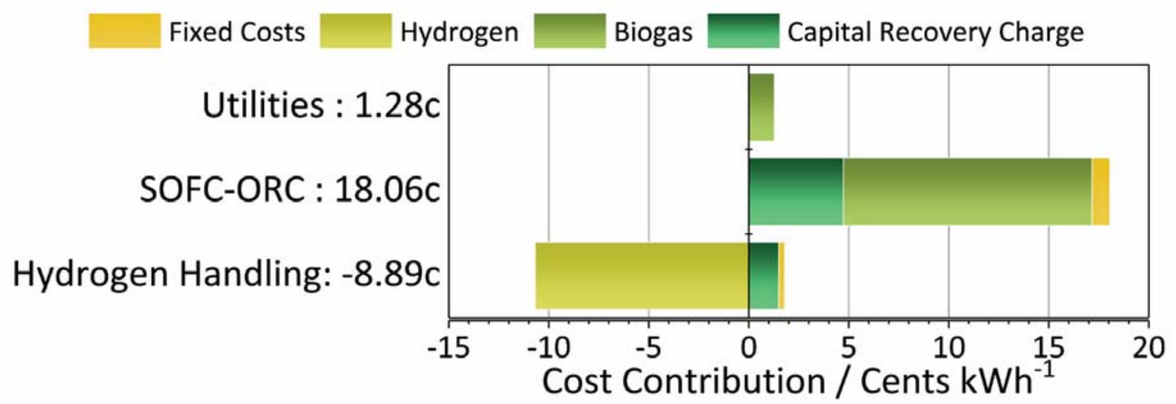

Figure 2: Cost contribution of each process area towards the BESP for the CHHP process

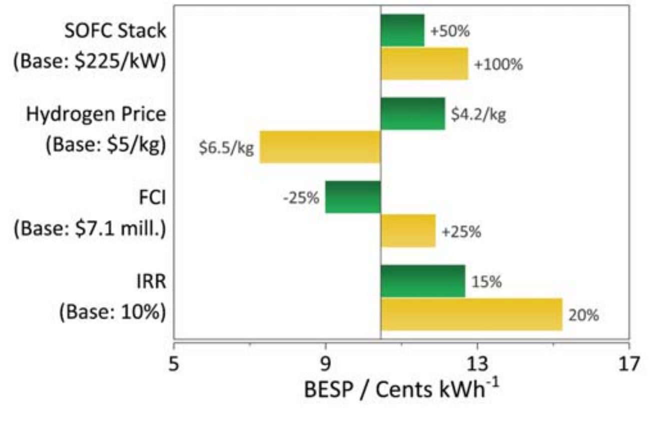

Figure 3: Impact of variation of the techno-economic model parameters on the BESP for the CHHP process

4. Conclusions

In this work, the poly-generation CHHP process was detailed. SOFC was directly coupled with ORC and WGS producing a net power output of 2.3 MW and 50 kg/hr of hydrogen. The key difference in SOFC design in comparison to the CHP process, is omitting the after-burner, which affected its efficiency and voltage.

The calculated electricity efficiency of the SOFC was 47%, while the voltage was 0.7 V. These values are slightly lower when compared to the SOFC in the CHP process. However, since hydrogen is also produced in this process, this process is profitable with a BESP of 10.45 ¢/kWh. This BESP value is similar to the US electricity price in 2017, and proves that the proposed CHHP process is indeed feasible.

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