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Waste2Watts: Techno-economic Feasibility of Biogas-fed SOFC Power System Integrated with Biogas Cleaning Unit and Carbon Capture Technologies

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Solid oxide fuel cell (SOFC) systems show immense potential for efficient biogas utilization, which can significantly reduce carbon emissions by integrating with biogas cleaning units and carbon capture technologies. Despite the significant benefits, the high cost of the integrated system presents a challenge. Therefore, a techno-economic assessment is necessary to evaluate the feasibility of the integrated system and provide guidelines for cost reduction. The ideal capacity for an integrated biogas-fed SOFC power system ranges between 20 kW to 200 kW. Firstly, a comparison of different biogas types and stack technologies is conducted to evaluate the system performance. Secondly, a techno-economic investigation of the feasibility of different system designs is performed by comparing different carbon capture technologies with various biogas cleaning units. The study results can facilitate the optimization of the integrated system's design and operation and pave the way for large-scale implementation of SOFC technology in the energy industry.

Introduction

As a promising power generation technology, the solid oxide fuel cell (SOFC) system demonstrates high electrical efficiency and overall efficiency in cogeneration mode. Operating at high temperatures (> 680 ˚C), SOFCs cogenerate high-quality heat and can be integrated with different industry facilities. Furthermore, SOFC technology demonstrates high fuel tolerance, including hydrogen, natural gas, ammonia, LPG, etc. Unlike other fuel cell technologies, SOFC systems can also tolerate impurities in the fuel, e.g., CO_2, N_2 or even a small amount of O_2. Besides, the compact system configuration makes SOFC system of great potential in the decentralized application.

In the context of the Paris Agreement, more and more solutions to replace fossil fuels have been proposed, where biogas is considered as one promising alternative. Biogas generally contains several impurities, making its application limited in the fuel cell technology field. Removing all the impurities and making it compatible for all the fuel cell technologies would be expensive. Whereas, since SOFC has high tolerance in fuel impurities, keeping certain harmful impurities under safe thresholds with a biogas cleaning unit and injecting the purified biogas into the SOFC system will be less costly. In this case, a biogas-fed SOFC system integrated with a biogas cleaning unit can be considered as a promising renewable technology by avoiding fossil fuel use and converting biowaste into electricity and heat.

Although biogas is produced from a renewable source, its use in SOFCs still generates CO_2 emissions when it is fed with biogas. To realize carbon neutrality or even being carbon negative in a biogas-fed SOFC system, carbon capture (CC) technology is introduced to meet the net-zero carbon emission target in 2050. One conventional carbon capture storage (CCS) technology is the calcium looping system, which uses $CaO/CaCO_3$ in a carbonation-calcination loop to separate and capture the CO_2 from the exhaust gas (1). This type of technology is quite mature for large-scale applications and has been widely used in thermal power plants for the desulfurization and denitrification of exhaust. Novel technology based on sodium carbonate solution is capable of not only carbon capture, but also biogas cleaning (2). For the carbon capture utilization (CCU) technology, the Fischer-Tropsch (FT) synthesis can convert CO_2 with hydrogen into syngas via electrochemical or thermochemical catalytically driven processes (3).

In this study, one biogas-fed SOFC power system is proposed with capacity ranging from 20 kW to 200 kW. The techno-economic analysis of different biogas cleaning technologies and CC technologies will be performed. Two operation modes of the SOFC system are considered: (1) hot recirculation mixed before the reformer, (2) cold recirculation mixed before the reformer. 30 optimal operating points of the SOFC system are selected to perform techno-economic analysis with three indicators, capital expenditure (CAPEX), operating expenditure (OPEX) and levelized cost of electricity (LCOE). The biogas-fed SOFC system integrated with biogas cleaning unit, different CCS and CCU systems is then investigated to derive a feasible system design.

System configuration

SOFC system

The SOFC system is composed of seven parts: stack, burner, heat exchange network, external reformer, compressors. The SOFC stack model is based on the product from our industry partner SolydEra. The operating parameters of the stacks are listed in Table I, while the fed biogas is composed of 57 vol.% CH_4, 37 vol.% CO_2, 4.74 vol.% N_2 and 1.26 vol.% O_2, which is generated from agricultural biowaste. By varying the recirculation ratio (RR, 1% to 90%), external reforming temperature (300 to 800 °C) and fuel utilization (UFF, 65%, 75% and 85%), the operating maps of the system were derived.

TABLE I. Operating parameters of SolydEra anode-supported cell stack.

Stack Temperature [°C]	Maximum fuel utilization	Maximum oxygen utilization	Maximum current density [A/cm^2]
[680, 800]	85%	30%	0.5

Two plant concepts have been considered: (1) hot recirculation mixed before the reformer (HB, Figure 1), (2) cold recirculation mixed before reformer (CB, Figure 2). Based on the existing operating maps of two schemes in the previous research, five optimal operating points of each scheme are selected to perform the techno-economic analysis.

Meanwhile, considering that it is unrealistic to increase the recirculation ratio of a real SOFC system to 80% or even higher, those operating points are ignored in techno-economic analysis.

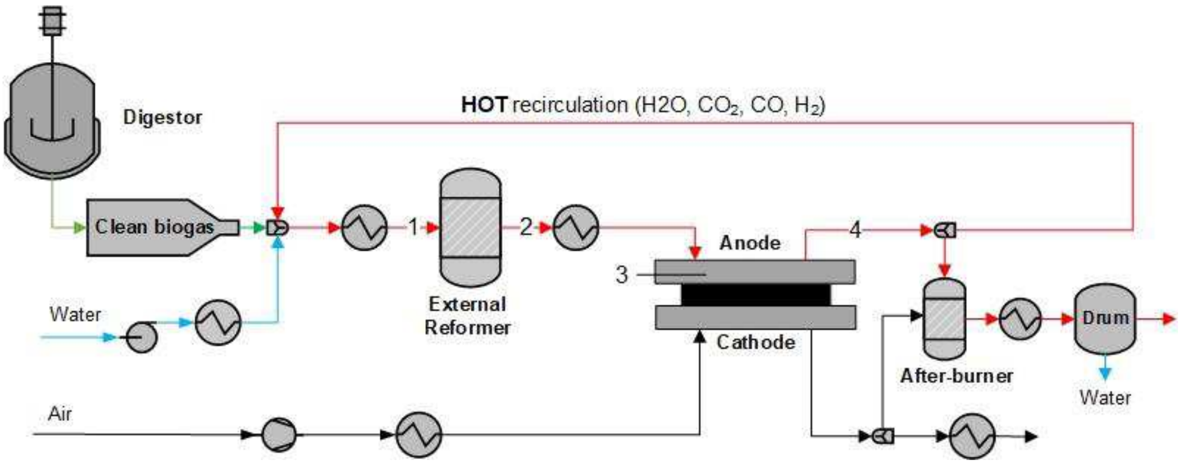


Figure 1. The scheme HB with hot recirculation mixed before reformer.

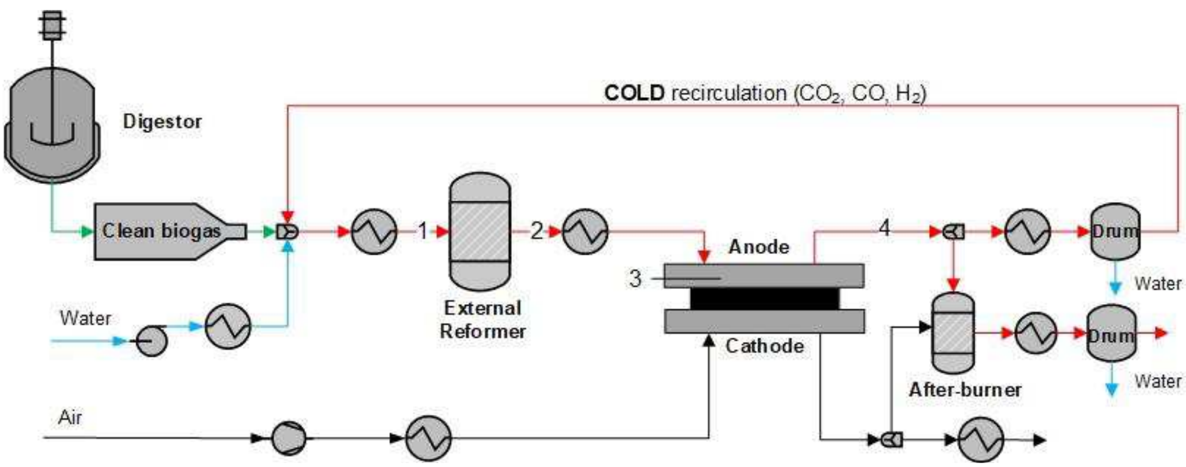


Figure 2. The scheme CB with cold recirculation mixed before reformer.

<u>Carbon capture system</u>

Based on the pathways to treat carbon dioxide, carbon capture technologies can be divided into carbon capture utilization (CCU) and carbon capture storage (CCS). In this study, a CCU system based on Fischer-Tropsch (FT) synthesis and two CCS systems based on calcium looping (CaL) and sodium looping (SL) are proposed and techno-economically compared.

<u>FT based CCU system.</u> This system utilizes CO_2 to synthesize hydro-carbons with a high-temperature calcium recovery loop process for CO_2 capture (3). The CCU system mainly consists of eight parts, namely (a) electrolysis section, (b) direct carbon capture (DAC) system, (c) thermal integration section, (d) reverse-water-gas-shift (RWGS) section, (e) FT synthesis section, (f) syngas compression section, (g) distillation section and (h) afterburn combustor. The final carbon capture efficiency of such a complicated system is 67.2% at relatively low CAPEX and OPEX for large scale application.

CaL based CCS system. The proposed calcium looping system is a post combustion CO2 capture system which is generally applied for existing coal power plant (1). It consists of two reactors, the carbonator and the calciner, where the reversible carbonation and calcination reactions happens based on the following equations:

$$CaO(s) + CO_2(g) \rightarrow CaCO_3(s),\ \Delta H_{298K} = -178\ kJ/mol \quad [1]$$

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g),\ \Delta H_{298K} = +178\ kJ/mol \quad [2]$$

With CO_2 capture efficiency of 90%, the CAPEX and OPEX is calculated based on the CO_2 storage cost referring to the data collected in America (4).

SL based CCS system. Two aforementioned systems are generally utilized in big scale system. Sodium looping based CCS system proposed and validated by VTT demonstrates high carbon capture efficiency of 97% and much lower cost (2). This system works at low temperatures (below 100 ℃) and is capable of removing H_2S in the raw biogas as well. The system configuration is illustrated in Figure 3 and its main reaction is demonstrated below:

$$Na_2CO_3 + CO_2 + H_2O \rightarrow 2NaHCO_3 \quad [1]$$

$$Na_2CO_3 + 2H_2S \rightarrow 2NaHS + CO_2 + H_2O \quad [2]$$

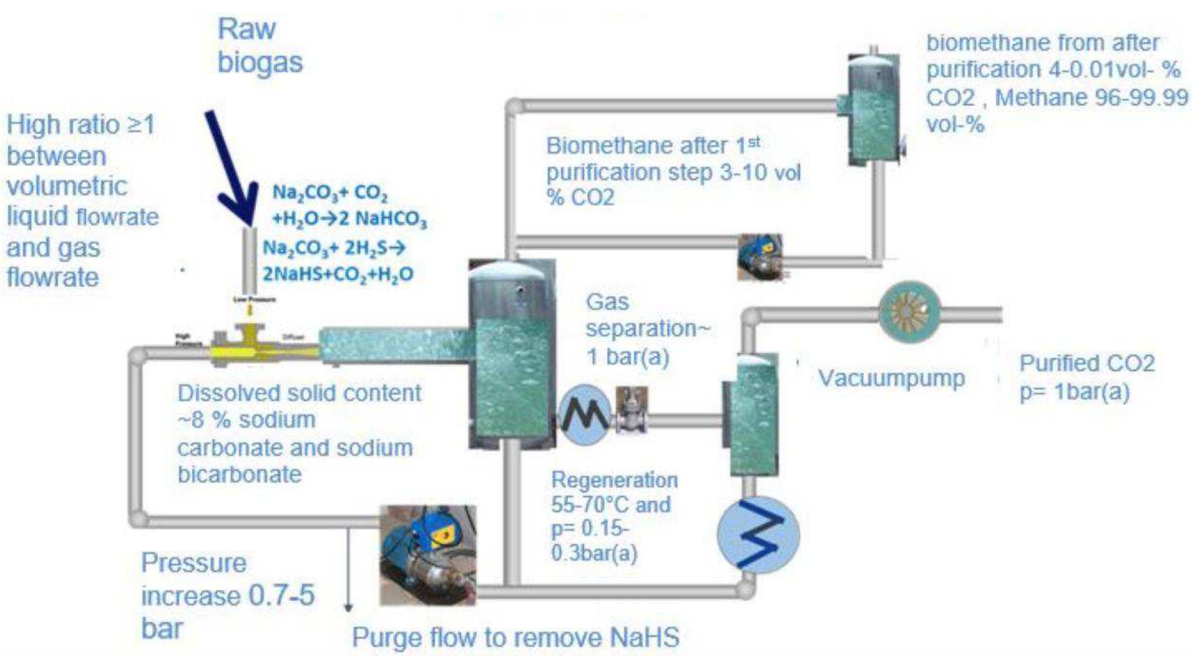


Figure 3. The system configuration of the sodium looping system for carbon capture and biogas cleaning (2).

Biogas cleaning unit

The clean section is set before the SOFC system inlet, which provides clean biogas to prevent stack degradation. Referring to Sara et al. (5), a biogas cleaning unit based on activated carbons to selectively remove siloxane compounds and H_2S is applied for a biogas-fed SOFC system at capacity of 58.3 kW, which is applied in our case by default for the comparison among different CCS and CCU technologies. As is illustrated in Figure 3, the novel sodium looping system is also capable of removing the H_2S in the biogas. In this case, an integrated system with two sodium looping systems and one SOFC system is proposed to validate their feasibility.

Economic assumption

When doing the cost evaluation of the system, costs of the components refer to various sources in different years, which are updated to the year 2018 using the ratio of CEPCI (Chemical Engineering Plant Cost Index) (6) values to account for the effect of inflation. All the global assumptions during the calculation are listed in Table II. Meanwhile, when calculating the CAPEX of the components, the engineering cost and the contingency cost are neglected. the capacity of the system is scaled to 20, 30, 40, 50, 60, 70, 80, 100, 150, and 200 kW, respectively, to investigate the scaling effect on the system cost. The unit of all the cost equations is euro.

TABLE II. Global assumptions for the techno-economic evaluation.

Parameters	Value
System lifetime [year]	20
Stack lifetime [year]	10
Annual production volume of stack [m^2]	30000
Year referred	2018
CEPCI (2018)	603.1
Fuel price [USD/MBtu]	9.3
W2W cost target of clean section	1000
W2W cost target of the biogas-fed SOFC power system [€/kWe]	2500

Concerning stack, stack enclosure, stack power system, burner and heat exchangers, the cost equations are derived by CEA, France in the Deliverable 3.5 of the project ECo (Efficient Co-Electrolyser for Efficient Renewable Energy Storage).

The cost function of external reformer refers to a report published by the U.S. Department of Energy (7), which proposed a fuel cell system with a capacity up to 25 kW.

For compressors, all the compressors applied are regarded as centrifugal compressors. The material for the compressors is set as carbon steel by default, and their efficiency is set at 80%. The cost of a compressor consists of two parts, the compressor module cost and the electric driver cost, which are calculated according to the book written by Gael D. Ulrich (8).

The clean section is set before the SOFC system inlet, which provides clean biogas to prevent stack degradation. The cost function refers to the literature (5), which is based on the average yearly concentration of H_2S and equivalent D4-siloxane measured respectively at about 20 and 1 ppm in the biogas. Adsorption system based on activated carbon (either impregnated or mixed with metal oxides) is applied for biogas ultra-purification.

Results

Operating maps

The operating map of the biogas-fed SOFC system is demonstrated in Figure 4. The efficiency trends of two schemes with different fuel utilization factors, external reforming temperatures and recirculation ratios are similar, and their efficiency difference at the same operating points is neglectable. To achieve higher SOFC system efficiency, higher recirculation ratio, higher external reforming temperature and higher fuel utilization factor are required. Note that exorbitant high recirculation ratio (higher than 80%) is not favored, while it is also unrealistic to increase this parameter to 80% or even higher in practical situation. In this case, five practical and optimal operating points in each map are selected to perform techno-economic analysis.

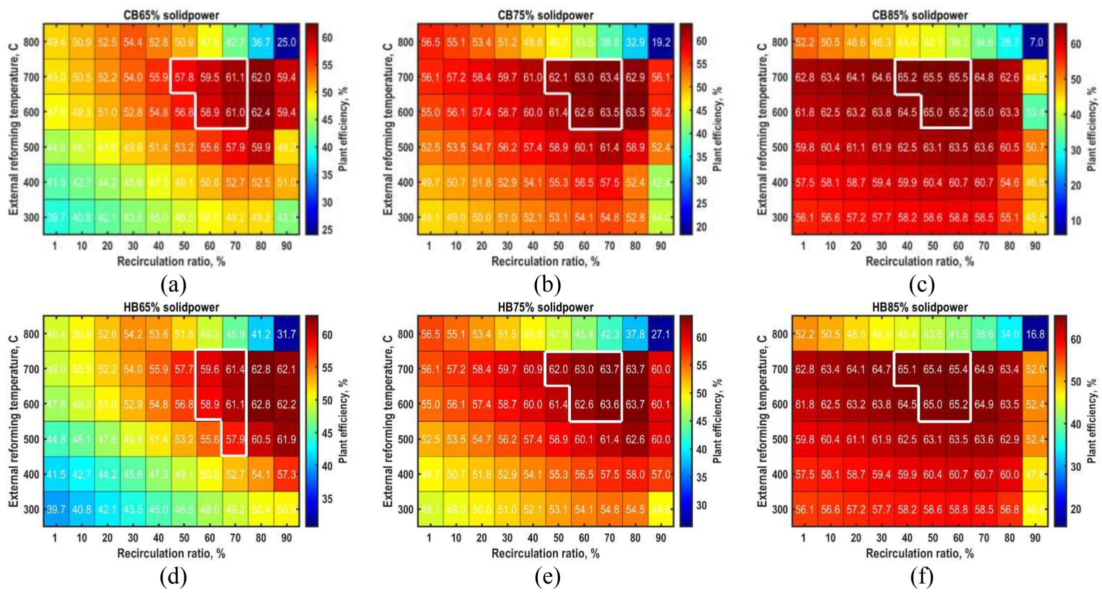


Figure 4. Electrical efficiency of the CB and HB schemes for biogas 1 at (a, d) 65% UFF, (b, e) 75% UFF, (c, f) 85% UFF with selected operating points marked with white frame.

<u>Techno-economic analysis of biogas-fed SOFC system</u>

As the core of the integrated system, biogas-fed SOFC system is analyzed techno-economically, and the results of LCOE at different operating points are shown in Figure 5. Generally, the higher UFF will contribute to the lower LCOE. At 20 kW system capacity, the lowest LCOE of 0.101 €/kWh appears in the CB scheme at UFF of 85%, RR of 40% and reforming temperature of 700 ℃. Notably, the LCOE in the HR scheme at the UFF of 65%, RR of 70% and reforming temperature of 500 ℃ is rather high with 0.116 €/kWh. According to Figure 4, the HB scheme operating point at UFF of 65%, RR of 70% and reforming temperature of 500 ℃ shows the lowest system efficiency, which leads to a higher demand for inlet fuel amount to maintain sufficient electricity output and hence a higher LCOE. On the other hand, increasing the system capacity from 20 kW to 200 kW only contributes to a LCOE decrease of 20%. For example, at the cold recirculation scheme with UFF of 85%, RR of 40% and reforming temperature of 700 ℃, the LCOE of 20 kW system is 0.101 €/kWh, while the LCOE of 200 kW system is 0.081 €/kWh. Ten-time bigger system only has 0.02 €/kWh lower LCOE, indicating that the scaling effect of the biogas-fed SOFC power system is not significant. Conclusively, although the operating points differ in price, there is no big variation in the cost structure of each point considering the same calculating methods. In this case, the further techno-economic assessment is based on the best operating point (CB scheme at UFF of 85%, RR of 40% and reforming temperature of 700 °C) and the worst operating point (HB scheme at UFF of 65%, RR of 70% and reforming temperature of 500 °C).

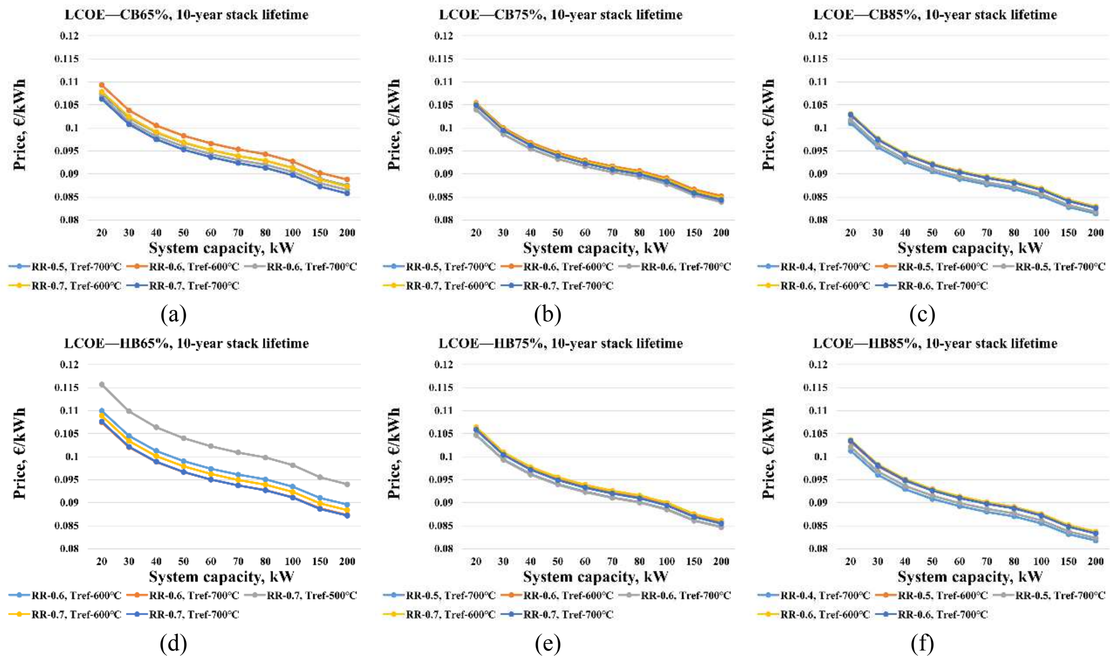


Figure 5. LCOE of the CB scheme and HB scheme with (a, d) 65% UFF, (b, e) 75% UFF, (c, f) 85% UFF, whose stack will be replaced for only one time in 20 years.

To figure out the key factors in the LCOE, we break down the LCOE results, as is shown in Figure 6. At different operating points, the structures of the LCOE are almost the same. Biogas cost always takes up the biggest contribution of higher than 45%, while the contribution of other parts is lower than 10%. Meanwhile, biogas cost increase with the system capacity extension, which is the same as the situation of stack-related cost, including stack cost, stack replacement cost, stack enclusure cost and stack power system cost. The contribution of stack-related cost increases from 17.8% at 20 kW system capacity to 22.1% at 200 kW system capacity. In this case, there are mainly two ways to decrease the system cost, (1) upgrading the biogas generation technology for lower cost and (2) decreasing the cost of the whole stack section.

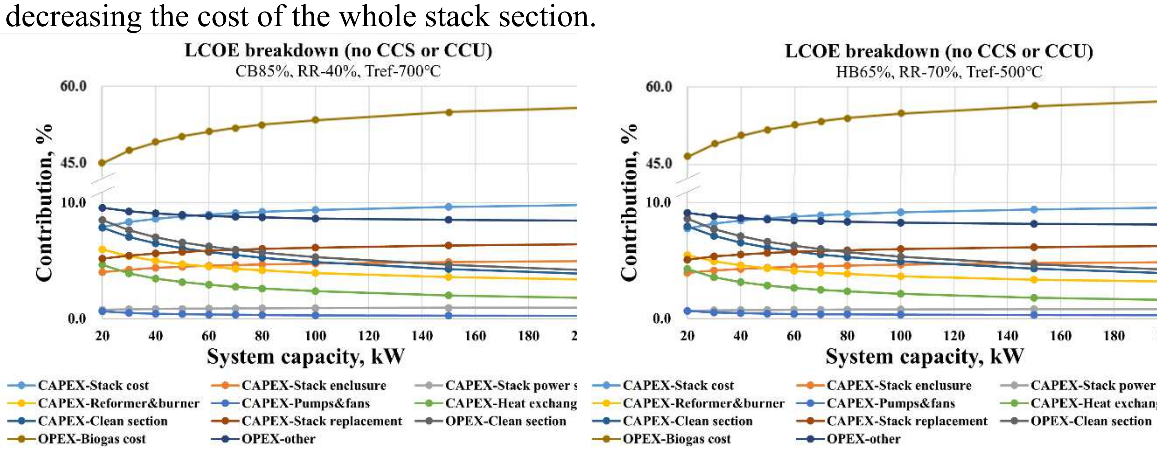
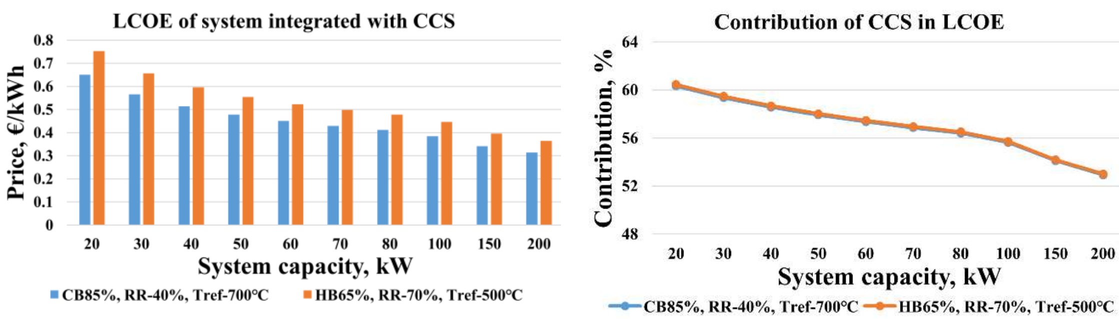


Figure 6. LCOE breakdown at two extreme operating points with replacing stack for one time in 20 years.

Techno-economic analysis of system integrated with conventional CC technologies

CaL based CCS system. Figure 7 demonstrates the LCOE of the system integrated with CCS and the contribution of CCS in LCOE. According to Figure 7 (a), because of the low electrical efficiency in the HB scheme with UFF of 65%, RR of 70% and reforming temperature of 500 °C, its LCOE is almost 0.1 €/kWh higher than that of the CB scheme with UFF of 85%, RR of 40% and reforming temperature of 500 °C. At the system scale of 200 kW, the integration of CCS technology increases the LCOE (CB85%, RR-40%, Tref-700 °C) from 0.081 €/kWh to 0.314 €/kWh. On the one hand, the scaling effect is quite obvious. For CB scheme, the LCOE decreases from 0.651 €/kWh to 0.314 €/kWh. On the other hand, Figure 7 (b) indicates that even at the system capacity of 200 kW, the contribution of CCS subsystem in LCOE is still as high as 53% regardless of operating points. Conclusively, the cost of CaL-based CCS technology is still unacceptable at the kW-level SOFC system.

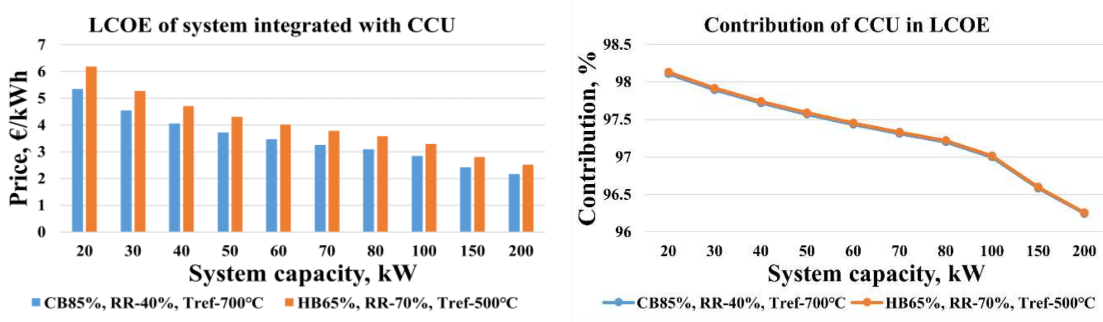


(a) (b)

Figure 7. Impact of the integration of CCS technology: (a) LCOE results of the integrated system with CaL based CCS system, (b) contribution of CaL based CCS system in LCOE.

FT based CCU system. The LCOE of the system integrated with CCU technology and the contribution of CCU subsystem in the LCOE are demonstrated in Figure 8. It is indicated that CCU technology is much more expensive than CCS technology. Similarly, the low efficiency of HB scheme (HB65%, RR-70%, Tref-500 ℃) results in higher carbon emission, which hence leads to the higher LCOE comparing with CB scheme (CB85%, RR-40%, Tref-700℃). As is indicated in Figure 8 (a), for CB scheme, the scaling effect will decrease the LCOE from 5.341 €/kWh at system capacity of 20 kW to 2.168 €/kWh at system capacity of 200 kW, where the decrease rate is 59.4%. Whereas, the fact that CCU takes up more than 96% LCOE regardless of system capacity indicates that the integration of CCU in the biogas-fed SOFC system is barely feasible.

Conclusively, the conventional FT technology for CCU and CaL technology for large-scale CCS are not applicable for kW-level biogas-fed SOFC system, in which case novel and cheap carbon capture technology should be exploited.

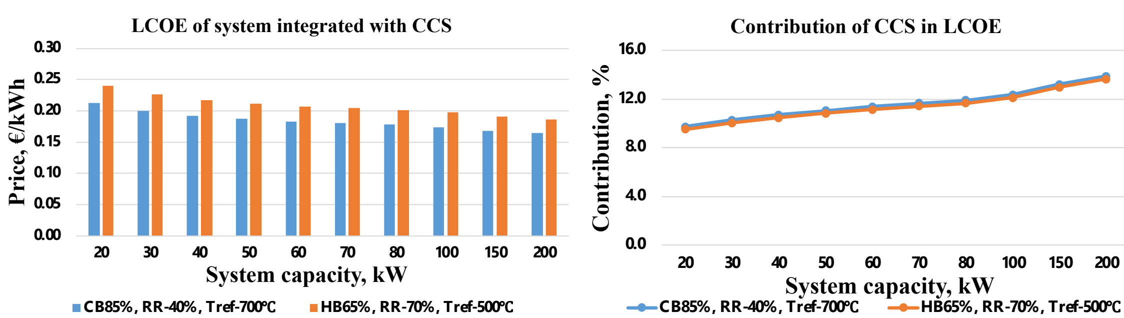


(a) (b)

Figure 8. Impact of the integration of CCU technology: (a) LCOE results of the integrated system with FT based CCU system, (b) contribution of FT based CCU in LCOE.

<u>Techno-economic analysis of system integrated with SL-based technology</u>

<u>SL-based CCS technology</u>. According to the aforementioned techno-economic analysis, large-scale and conventional CaL-based CCS system and FT-based CCU system are not feasible. For comparison, the techno-economic performance of SL-based CCS technology is demonstrated in Figure 9. According to Figure 9 (a), applying SL-based CCS system will increase the LCOE to around 0.2 €/kWh, and the difference between two extreme cases is around 0.03 €/kWh regardless of scaling effect. Moreover, the scaling effect for this case is relatively small, with only 22% reduction from 20 kW capacity to 200 kW capacity. In Figure 9 (b), it is shown that CCS contribution in LCOE increases with the system capacity, from around 9.6% at 20 kW to around 13.6% at 200 kW in both HB and CB schemes. This indicates that when the system capacity increases to MW level, cost of the SL-based CCS system may be the main investment of the whole system. Conclusively, SL-based CCS technology is a techno-economically feasible way for biogas-fed SOFC system to achieve low carbon emission with lower and acceptable LCOE of around 0.2 €/kWh.



(a) (b)

Figure 9. Impact of the integration of SL based CCS system (a) LCOE results of the integrated system with SL based CCS system, (b) contribution of SL based CCS system in LCOE.

<u>SL-based technology for both CCS and biogas cleaning</u>. The LCOE results of bioags-fed SOFC system integrated with two SL systems for both CCS and biogas cleaning unit is demonstrated in Figure 10. Comparting Figure 10 with Figure 9 (a), the LCOE of applying two SL-based systems is slightly higher than only utilizing one SL-based system for CCS. When SL-based system is applied as the biogas cleaning unit, not only H_2S but also CO_2 will be removed. Since CO_2 takes up 37% in the biogas, the amount of the

chemical materials and the size of the system are higher than those of the original biogas cleaning unit, which only considers siloxane and sulfur contaminants with much lower concentration. In this case, the cost of applying SL-based system for biogas cleaning unit is not favored.

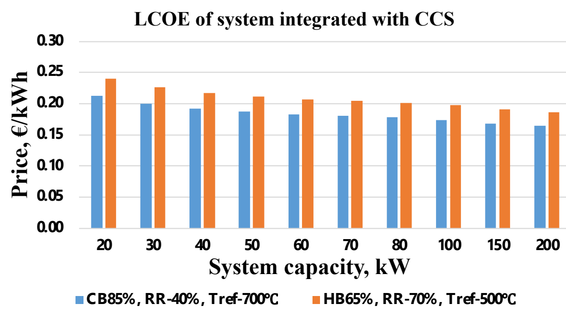


Figure 10. LCOE results of the system integrated with two SL systems for both CCS and biogas cleaning.

Conclusion

According to the operating maps of the biogas-fed SOFC system, 30 optimized operating points are picked out to perform techno-economic assessment according to the capital expenditure (CAPEX), operating expenditure (OPEX) and levelized cost of electricity (LCOE). The results validate (1) two extreme operating points of the biogas-fed SOFC power system, (2) the key components that affect the system cost most, (3) the feasibility of three carbon capture technologies, calcium looping (CaL) based carbon capture storage (CCS) technology, Fischer-Tropsch (FT) based carbon capture utilization (CCU) technology and sodium looping (SL) based carbon capture storage technology.

Operating point in the CB scheme with UFF of 85%, RR of 40% and reforming temperature of 700 °C demonstrates the lowest LCOE. By breaking down the LCOE, it can be concluded that LCOE is dominated by the biogas cost and stack-related cost (stack replacement cost, stack enclusure cost and stack power system cost). The biogas-fed SOFC power system integrated with CaL-based CCS system and FT-based CCU system, which is traditionally applied in large scale system, has the LCOE of higher than 2 €/kWh and 0.3 €/kWh, respectively. Contributions of two subsystem cost in LCOE are higher than 95% and 50% respectively. This indicates that the conventional large-scale CCS and CCU technology is not techno-economically feasible for kW-level biogas-fed SOFC system. SL-based system as a novel CCS technology only increases the LCOE to around 0.2 €/kWh. Although the scaling effect is not ideal, this still indicates that SL-based system is a feasible choice for kW-level biogas-fed SOFC system. SL-based system can also be utilized for biogas cleaning. However, considering the removal of CO_2 and contaminants requiring bigger system size and hence higher investment, its LCOE is higher than that of the case which applies conventional absorbent-based biogas cleaning unit and SL-based CCS system. This indicates that the SL-based system is not favored as a biogas cleaning unit.

Acknowledgments

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