Influence of Operating Parameters and System Design on Efficiency of Biomass and Biogas Based SOFC Systems

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The presented work investigates utilization of biogas and syngas from biomass gasification in different system designs. This is done using a thermodynamic SOFC model built in Aspen Plus. With the model, the influence of different fuel pre-treatment and pre-reforming options are compared at a fixed stack size. Furthermore the effect of anode off-gas recirculation, as well as the choice of fuel utilization are studied. Results show, that depending on the fuel, system design and parameters the electrical efficiency of the fuel cell alone can vary between 35 and 71%. System AC net efficiencies reach from 30 to 64%. Finally a new system configuration is investigated, which is based on recovery of H_2 from the anode exhaust using a water gas shift membrane. For this new configuration an efficiency of 73% is calculated.

Introduction

With the recent COP 21 declaration many countries have dedicated themselves to a clear path towards de-carbonization. This requires major installation of wind and solar power. However, these only provide intermittent electricity. Thus, balance power has to be provided, ideally from renewable resources. Currently besides pumped hydro storage only biomass seems to be available in large enough quantity to provide significant renewable balancing power. A wide range of biomass feedstocks can be made available for power generation for example via anaerobic digestion or thermo-chemical gasification. Yet, resources are still limited. Hence, in order to maximize its potential the biomass has to be used at the highest possible efficiency. Electrochemical conversion, especially in SOFC, in general offers very high efficiency. However, also in SOFC systems the choice of the optimal system design and operating parameters can make a big difference. The presented work investigates utilization of biogas and syngas from biomass gasification in different system designs. This is done using a thermodynamic SOFC model built in Aspen Plus, which has been validated against literature data.

SOFC model

A detailed description of the SOFC model used in this work has been published in (1). The basic layout of the thermodynamic model is based on a model described in (2), while the cell parameters were taken from (3). Therefore, only a comparison to cell and stack performance of the well-known manufacturers Fuel Cell Energy (former Versa Power) and Forschungszentrum Jülich is presented in the following. For this purpose Figure 1 shows results obtained by Versa Power (4) and the SOFC model operating at identical temperatures, atmospheric pressure and pure hydrogen as shown in Table I.

TABLE I. Parameters for comparison of SOFC model with results from Versa Power.

Parameter	Value
Temperatures	600, 700, 800°C
Pressure	1.05 bara
Anode inlet	100% H_2
Fuel utilization	<10%
Cathode inlet	21% O_2, 79% N_2
Oxygen utilization	<1%

As is observable, despite the model is based on single cell data, the performance is much lower than the experimental data from (4).

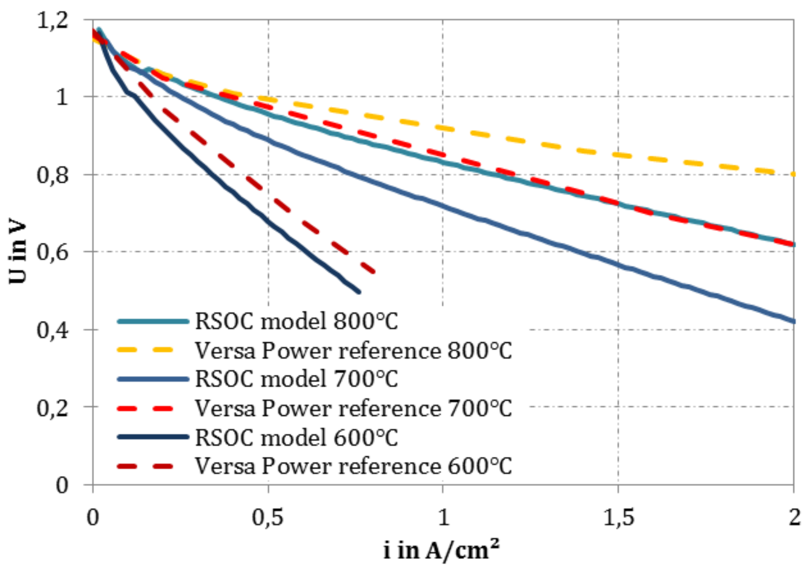

Figure 1. Comparison of the SOFC model and experimental single cell data from (4).

Thus a further comparison is shown in Figure 2. Here the model is operated at conditions as presented in (5), which are shown in Table II, for short stacks manufactured at the Forschungszentrum Jülich. As can be seen from the figure the model performance is almost identical to the stack performance at 700°C, while at 800°C the real stack performs slightly better than the model. Overall it can be concluded that at identical operating conditions the model shows slightly worse performance than the real stacks.

TABLE II. Parameters for comparison of SOFC model with results from Jülich.

Parameter	Value
Temperatures	700, 800°C
Pressure	1.05 bara
Anode inlet	80% H_2, 20% H_2O
Fuel utilization	0 - 60%
Cathode inlet	21% O_2, 79% N_2
Oxygen utilization	<1%

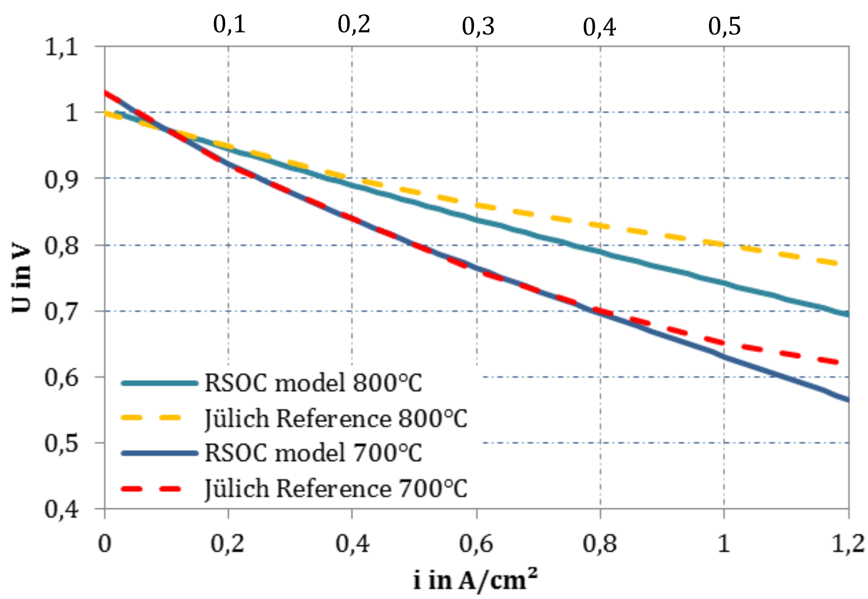

Figure 2. Comparison of the SOFC model and experimental short stack data from (5). The values shown at the upper x-axis resemble the respective fuel utilization.

System design and analysis

In the following different system configurations are compared. Figure 3 displays a simplified drawing of the system layout under study. Air enters the SOFC cathode after compression to operating pressure and passing the air preheater. Fuel is also first brought to operating pressure, guided through a ZnO desulphurization bed, followed by the fuel preheater. Further gas cleaning measures are not investigated in detail, as described later. After passing through the SOFC the depleted air and fuel streams are mixed in a catalytic combustor. The combustor flue gas is split to supply both air and fuel preheaters with the required heat. Residual heat in the flue gas is assumed to be used for production of hot water or steam. Before entering the anode the fuel stream is:

(a) externally reformed by either auto-thermal catalytic partial oxidation (CPOX) using a small amount of preheated cathode air, or steam reforming (ext. ref.) by direct thermal coupling to the post-combustor
(b) mixed with a recirculated anode exhaust stream in order to promote internal reforming (int. ref.)

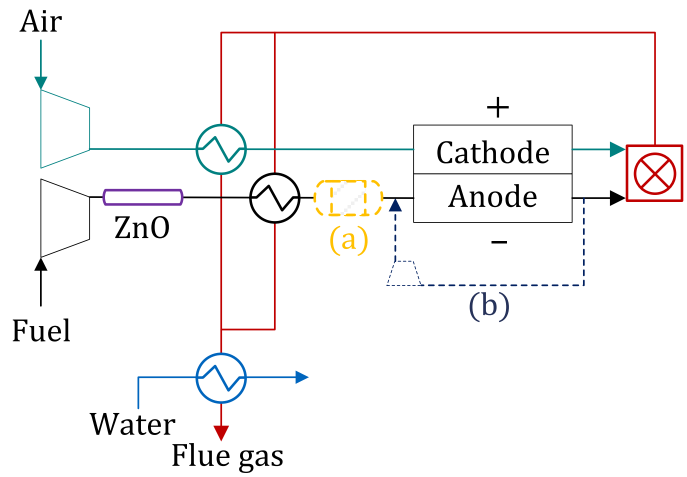

Figure 3. Simplified schematic drawing of the system layout.

Table III shows the general assumptions for the simulations. For the analysis the stack single pass fuel utilization (FU) is in always limited to 80%, since inhomogeneity in the fuel distribution along the stack could otherwise cause severe degradation. Therefore higher global FU values are only achievable when using anode exhaust recirculation. Furthermore, for almost all cases the global FU is generally limited to a value where the anode exhaust still contains at least 5%-mol. residual fuel.

TABLE III. General assumptions for the system analysis.

Parameter	Value
Fuel inlet temperature	750°C
Fuel outlet temperature	800°C
Air inlet temperature	700°C
Air outlet temperature	800°C
Average operating temperature	775°C
SOFC operating pressure	1.05 bara
SOFC active area	100 m^2
Blower isentropic efficiency	0.75
Mechanical + motor efficiency	0.95
Inverter efficiency	98%
Air composition	21% O_2, 79% N_2
Oxygen utilization	≤50%
Fuel electrons input	8.0 mol/s
Single pass stack FU	≤80%
Minimum outlet fuel concentration	≥5%-mol.

Simulation results

Gasification syngas

First of all the conversion of syngas from biomass gasification is studied. Since the gasification syngas typically exits the gasifier with a composition already close to thermodynamic equilibrium at 700-800°C basically no pre-reforming is necessary. Thus, after removal of contaminants (S, Cl, tars and others) the syngas can be fed directly to the anode. Detailed analysis of gas cleaning is beyond the scope of this work. Relevant information can be found in refs. (6-8). The fuel composition, similar to (9), and fuel energy input can be seen in Table IV. The fuel flow is adjusted in order to achieve the same amount of electrons available for electrochemical conversion.

TABLE IV. Syngas composition from woody biomass gasification (9).

Parameter	Value
Fuel power	936.7 kW_{LHV}
Fuel flow	7.27 mol/s
H_2	25%
CO	10%
CO_2	10%
CH_4	5%
H_2O	50%

Figure 4 shows the results of the parameter study for a system without recirculation and a recirculation rate of 50% (R=0.5). These are results of the SOFC only, yet without including inverter losses and auxiliary consumption (mainly blowers).

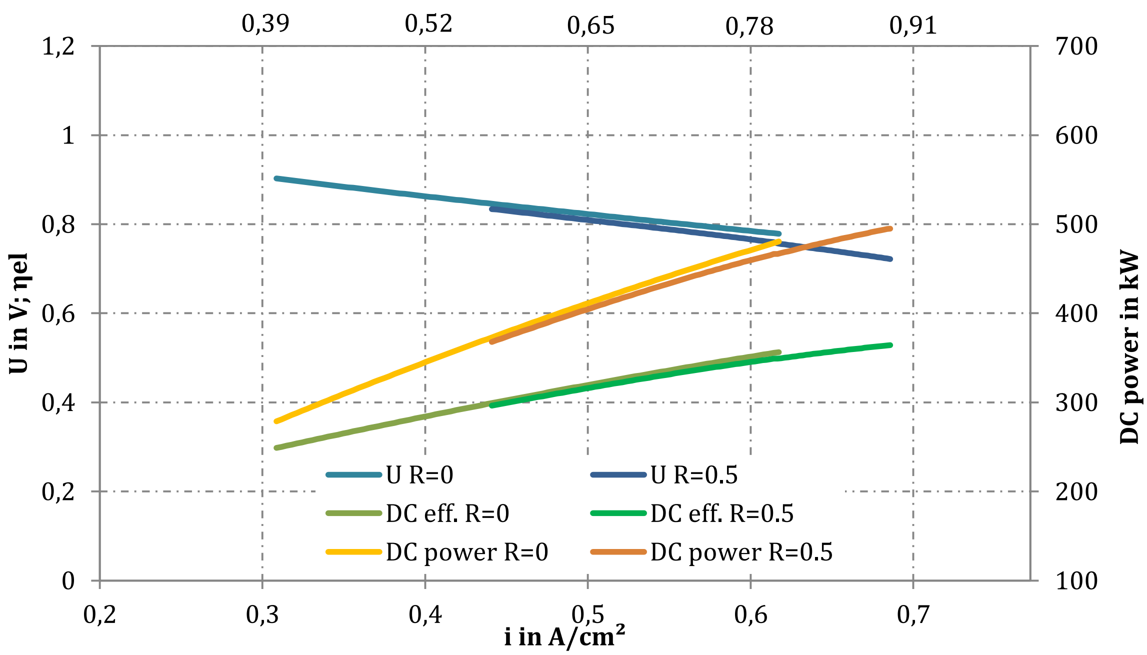

Figure 4. Results of the parameter study for SOFC operated on gasification syngas. The values shown at the upper x-axis resemble the global fuel utilization.

The results show that in the syngas case the recirculation rate slightly lowers the cell voltage due to the dilution with additional steam and CO_2. Thus, until a global FU of 80% the system performs better without recirculation. However, due to the restriction to 80% single pass FU in order to achieve maximum power output recirculation is necessary. The maximum achievable global FU is 88%, before the anode exhaust reaches the dilution limit.

Biogas from anaerobic digestion

In contrast to syngas biogas from anaerobic digestion mainly consists of a mixture of CH_4 and CO_2. CH_4 concentrations typically range from 50-70%. Here as a worst case scenario 50% is assumed as displayed in Table V. It is already observable from the table that in order to achieve an equivalent amount of available electrons the required energy input (LHV) is much lower for biogas than for syngas. Also in this case detailed analysis of cleaning is beyond the scope. Further information biogas generation and cleaning may be found in (10).

TABLE V. Exemplary composition of biogas from anaerobic digestion.

Parameter	Value
Fuel power	802.7 kW_{LHV}
Fuel flow	2.0 mol/s
H_2	0%
CO	0%
CO_2	50%
CH_4	50%
H_2O	0%

Figure 5 shows the performance results of the SOFC operated in with different reforming approaches as explained above. As is to be expected, using CPOX the performance is lower than for the other options, since a share of the fuel is already consumed during the auto-thermal CPOX. Despite the fact that the fuel energy content (LHV) does not significantly change during the CPOX, the exergy content in the form of available electrons is reduced by more than 24%. Therefore the achievable maximum power density reduces. Furthermore the voltage is lowered by dilution of the fuel with combustion products and N_2.

Comparing the cases of external steam reforming and internal steam reforming with anode exhaust recirculation several effects are observable. First of all the allowed FU range is very different for both cases. For external reforming the global FU is limited by the maximum single pass FU of the stack. In the case of internal reforming there is a minimum FU of about 75%, which is determined by the risk of carbon deposition and too high air utilization for lower FU values. Secondly, for the internal reforming the I-V curve is shifted towards higher fuel utilizations. This is attributed to the recirculation of unconverted fuel, which overall increases the average concentration of fuel at equivalent global FU values and thus the Nernst potential. For internal reforming in the plot also an exception has been made to allow outlet concentrations of less than 5%-mol. of residual fuel. Above a global FU of 88% (stack FU of 80%) the recirculation rate is increased from 50 up to 90% (above 80% the outlet fuel concentration becomes <5%) in order to examine the dilution of the inlet fuel with the reaction products H_2O and CO_2 at very high global FU. Above a FU of 92% the dilution starts to dominate the I-V behavior and the overall power output decreases.

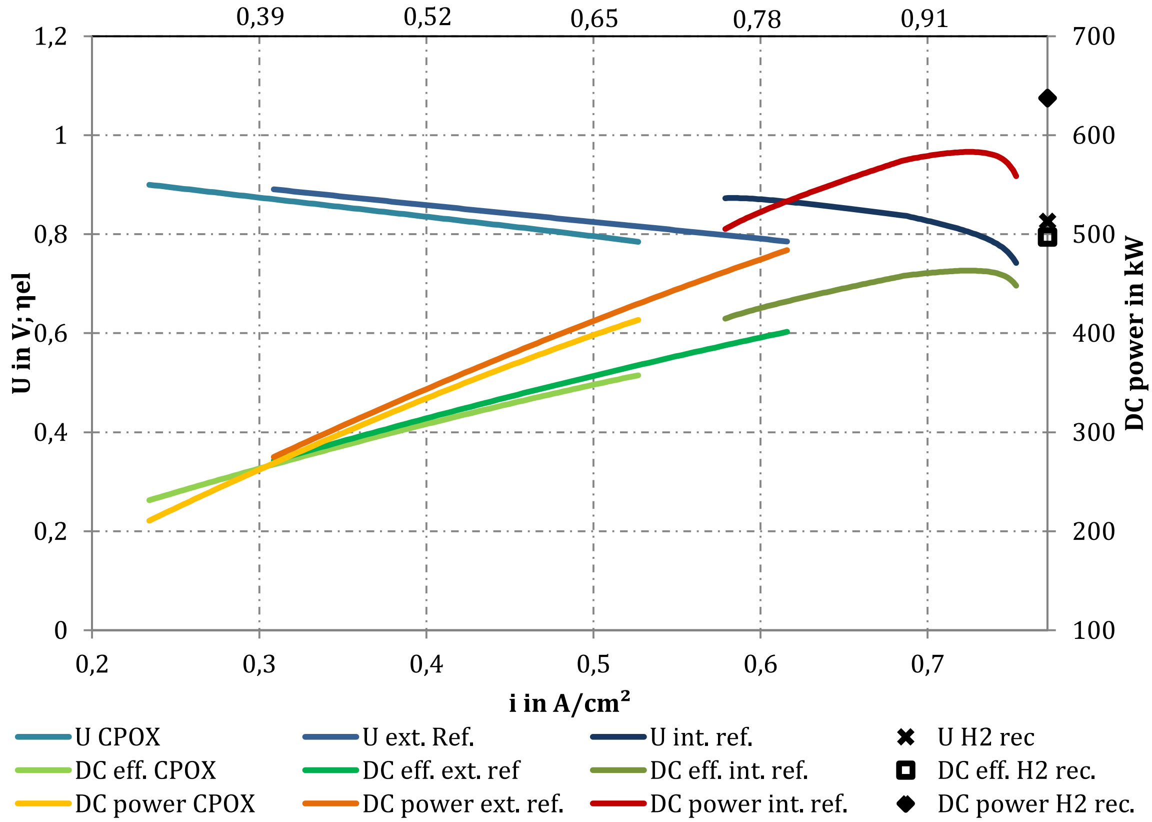

Figure 5. Results of the parameter study for SOFC operated on biogas from anaerobic digestion. The values shown at the upper x-axis resemble the global fuel utilization.

To counter the dilution effect and enable a global FU of close to 100% Schlitzberger proposed a new system layout as shown in Figure 6 (11). Here this configuration is adapted for the conversion of biogas. The residual CO in the anode exhaust generated by internal/external reforming is converted in a water gas shift membrane unit, which is purged with the inlet biogas on the permeate side, according to Eq. 1.

$$CO + H_2O \rightarrow CO_2 + H_2 \quad [1]$$

During this process the H_2 permeates through the membrane into the biogas. Thus the residual available electrons are re-transferred into the inlet fuel thereby and again into the SOFC. Hence, ideally the global FU becomes independent of the stack FU and the anode exhaust recirculation rate and is only dependent on the separation efficiency of the membrane. Furthermore, using an ideal membrane finally pure CO_2 can be obtained. Simulation results for this configuration with a stack FU of 50%, an anode exhaust recirculation of 30%, which is just enough to prevent carbon deposition, and consequently a H_2 transfer of 2.8 mol/s (to achieve 100% global FU) are shown on the right side of Figure 5. For this first analysis the membrane is assumed as an ideal membrane, which exclusively permeates H_2 without significant pressure drop. The simulation results are depicted in Table VI. Despite the high current density of 0.77 A/cm² due to the avoided concentration losses the operating voltage is 0.82 V and the calculated DC efficiency rises up to 78.8%. This is 7.4 %-points higher than the maximum value for the anode exhaust recirculation case.

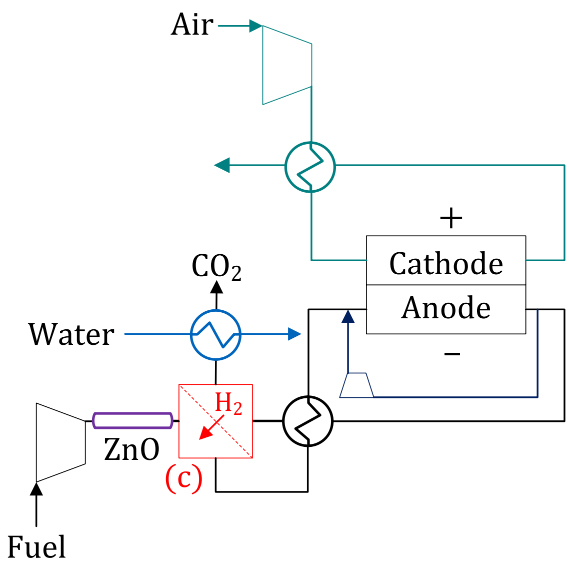

Figure 6. Simplified schematic drawing of SOFC system with water gas shift membrane and H_2 recovery for increased fuel utilization.

TABLE VI. Simulation results for the SOFC system with H_2 recovery.

Parameter	**Value**
Operating voltage	0.82 V
Current density	0.77 A/cm²
DC output	632.3 kW
Inverter losses	-12.6 kW
Air blower	-31.3 kW
Biogas blower	-1.3 kW
Anode exhaust recycle blower	-0.7 kW
Net AC output	586.3 kW
Net AC efficiency	73.0%

Considering auxiliary consumption by blowers and inverter losses the net AC output in this configuration reaches 586.3 kW, which resembles a net efficiency of 73.0%. The highest net AC efficiency calculated for the conventional internal reforming case is 64.3%. The fairly low auxiliary consumption in both cases is due to the cooling effect of the internal reforming. In the external steam reforming case due to a larger cooling air demand because of the missing cooling effect the efficiency becomes only 49.0%, whereas in the CPOX case the maximum AC efficiency is even as low as 43.1%. For syngas operation also a very high cooling air demand is necessary. Furthermore as described above the exergy content of syngas is lower than for biogas. Therefore the maximum efficiency of the SOFC operating on syngas is calculated as 43.9%.

Summary

In this study several system configurations for utilization of biogenous fuels in SOFC are investigated using a thermodynamic SOFC model built in Aspen Plus. An initial comparison to experimental data from well-known manufacturers yields that the model performs similarly or slightly worse than state-of-the-art SOFC stacks. Based on this result the utilization of a typical syngas from biomass gasification, as well as typical biogas from anaerobic digestion is examined. In the case of syngas the original solid biomass fuel is already reformed. For biogas several different reforming options are investigated. Findings are that the efficiency largely depends on the type of fuel used, as well as the system configuration. Due to the requirement of large amounts of cooling air syngas and CPOX the maximum net obtainable efficiency found during the parameter studies is around 30-44%. Steam reformed biogas enables efficiencies of up to 49%, while internal reforming with anode exhaust recirculation can increase the efficiency to above 64%. Since it is found that the internal reforming approach is essentially limited by the inability to convert all the fuel electro-chemically at high efficiency a new system configuration is adopted, which was first proposed by Schlitzberger (11). The system is based on recovery of unconverted fuel via a water gas shift membrane. Simulation results for this new configuration, based on the assumption of an ideal membrane behavior, show the potential to reach net efficiencies of up to 73% when operated on biogas.

Acknowledgements

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