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Integrated Gasification and Solid Oxide Fuel Cell System

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1 ABSTRACT

A novel gasification concept combining entrained flow gasification of coal and Solid Oxide Fuel Cells (SOFC) has been developed, simulated and evaluated in Aspen Plus®. The main characteristic of the concept is a recirculation of anode exhaust from the SOFC to the gasifier in order to substitute transport gas and gasification agent. At the same time a share of the unconverted fuel and heat from the anode outlet is chemically recycled and thus the cold gas efficiency of the gasifier is found to increase from 82.1% to 83.2%. However, the impact of the recirculation approach has been found to be limited due to the fact that too high flows of additional gas lead to a decrease in efficiency because of rising heat duty. The maximum electrical efficiency achieved in the coupled system reaches up to 62.8%.

2 INTRODUCTION

Integrated gasification power plants are a promising technology for future utilization of coal [1]. However, one major drawback is the efficiency of the Integrated Gasification Combined Cycle (IGCC) when compared to a conventional combined cycle due to the additional gasification step. Cold gas efficiencies of entrained flow gasifiers usually lie in the range of 78-82% [2]. Consequently the electrical efficiency of IGCC plants only range from 40%-50%. This efficiency range is similar to existing conventional coal fired power plants but at higher system complexity. To improve the system efficiency a novel gasification concept combining entrained flow gasification of coal and Solid Oxide Fuel Cells (SOFC) has been developed and evaluated.

3 SYSTEM CONCEPT AND MODELING

In this work the energy and mass balance of the novel system are studied using the simulation software Aspen Plus®. Process streams and heat integration are optimized using an exergy analysis approach [3-5].

In the system configuration under study, of which a schematic flow sheet is shown in Figure 1, an oxygen blown entrained flow gasifier is used to generate syngas (or product gas) from hard coal at a pressure level of 20bar and 1450°C. The gasifier model is based on a chemical equilibrium approach and has also been described and validated previously [6]. Oxygen is delivered from an air separation unit [6]. The gasifier consists of a gasification chamber, and a radiative syngas cooling and slag separation section, where in both sections saturated steam is generated at 100bar. After the syngas leaves the gasifier at 800°C coarse particles are separated in a cyclone. Then the syngas is further cooled to 370°C and cleaned in a sequence of warm gas cleaning steps. First fine particles and condensed alkali substances are removed in a sinter metallic filter. Afterwards Chlorine and Sulphur compounds are adsorbed in Sodium and Potassium carbonate and Zinc oxide beds. The warm gas cleaning approach has been selected due to the required purity of the syngas with regards to Sulphur compounds of below 1ppm, which is most easily achieved with Zinc oxide adsorbents [7]. Subsequently to the gas cleaning pressure losses in the gasifier and gas cleaning are compensated with a compressor. Then a varying share of the syngas is re-heated to 700°C and fed to the SOFC. The remainder of the syngas is provided for further purposes, such as utilization in a combined cycle, methane production or similar.

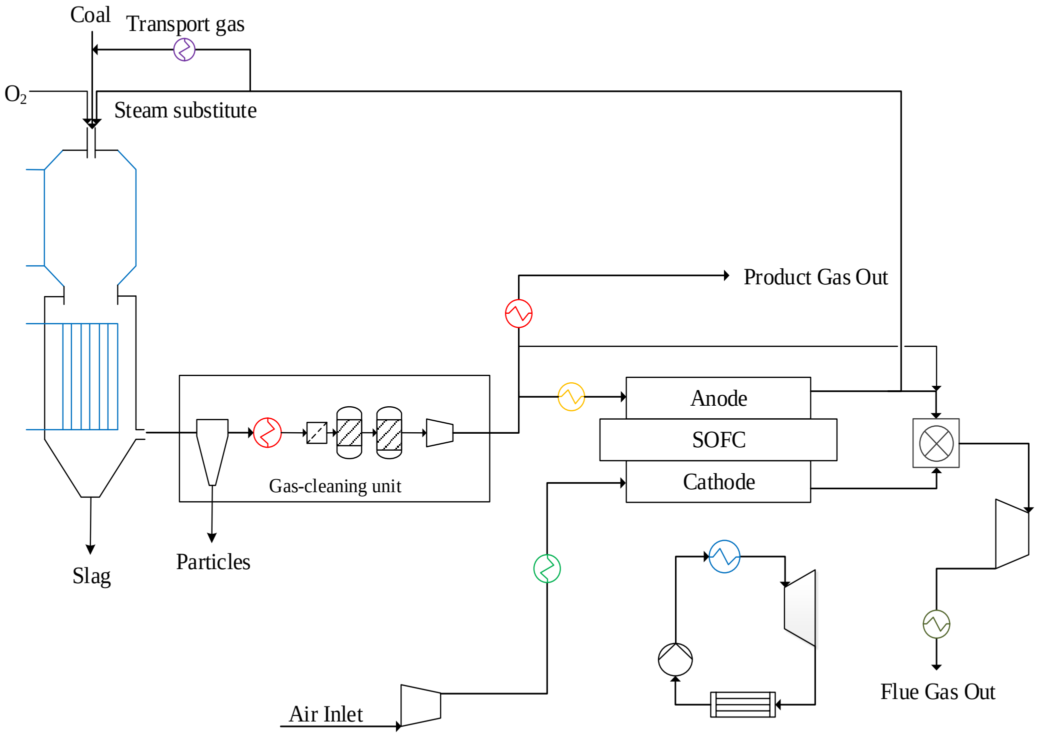

Figure 1: Schematic diagram of the proposed system configuration.

The SOFC model, which has been developed in the FCH-JU project SOFCOM, is based on a Gibbs free energy accounting approach and has been validated using manufacturer data [8]. In the SOFC the syngas is converted to electricity at a global fuel utilization rate of 85% whilst heating up to 1000°C. A portion of the resulting high temperature SOFC anode exhaust containing H_2O, CO_2, H_2 and CO is used to replace the coal transport gas, flame supporting natural gas and gasification agent in the gasifier. This is assumed to provide several advantages compared to a conventional entrained flow gasifier setup: No external transport gas or gasification agent is

necessary, and residual fuel is chemically recycled in the gasifier. Furthermore the heat contained in the exhaust reduces the amount of energy normally required to heat up the gasification agent, e.g. steam. In order to be utilized as transport gas a share of the anode exhaust is cooled to 150°C.
Fresh air is supplied to the cathode of the SOFC at 650°C. Cathode exhaust from the SOFC, which is oxygen depleted air at 1000°C, is combusted with the left-over anode exhaust and fresh fuel to reach a temperature of 1350°C and then expanded in a turbine before entering a heat exchanger to pre-heat the fresh air. Residual heat of the system is used to generate superheated steam at 100bar, which is fed to a steam turbine.
The main process parameters and assumptions are summarized in Table 1. As can be seen most parameters have been selected conservatively, according to present day technology [6]. Future plants with more sophisticated parameters would thus offer the possibility of performance improvement. The major challenge in this configuration is represented by the pressurized SOFC, which is currently not state of the art.

Table 1: Main process parameters and assumptions.

Gasifier			SOFC		
Gasifier inlet pressure	20	bar	Operating Voltage	0.8	V
Gasifier temperature	1450	°C	Fuel utilization	85	%
Gasifier outlet temperature	800	°C	Air pre-heat temperature	650	°C
Steam cycle and turbomachinery			Fuel gas inlet temperature	700	°C
Live steam pressure	100	bar	Outlet temperature	1000	°C
Live steam temperature	430-600	°C	Operating pressure	20.6	bar
Pinch points (minimum)	10	K	Pressure drops		
Condenser pressure	0.025	bar	Gasifier and gas cleaning	4.2	bar
Isentropic efficiency (all)	0.85	-	Air pre-heater (fresh air side)	0.4	bar
Mechanical efficiency (all)	0.98	-	Air pre-heater (flue gas side)	0.05	bar
Gas turbine TIT	1350	°C	HRSG (flue gas side)	0.05	bar
Gas turbine exhaust	670	°C	Other heat exchangers	<0.2	bar
Gas turbine pressure ratio	18.2	-	Pressure drop SOFC	0.4	bar

4 SIMULATION RESULTS

4.1 Heat integration

For the heat integration of the proposed system several limitations have been taken into account, especially with regards to a minimum number of heat exchanger connections and simplicity of stream arrangement in real systems. The optimized heat integration diagram is shown in Figure 2. The colors used refer to the heat exchanger colors as shown in Figure 1. From left to right streams are arranged in a sequence from high to low hot side (secondary flow) temperatures. First the gasifier and radiative syngas cooling are shown, which are achieved by generation of saturated steam from saturated liquid water. Due to the high temperature spread between hot and cold side this process is associated with very high exergy destruction, however, with present day materials no higher cooling temperatures are realistic. Following the evaporative cooling section hot anode exhaust and syngas after particle cleaning are used to superheat the steam and pre-heat the anode fuel flow. Here a heat exchanger split arrangement is necessary to satisfy the different heating demands. Fresh air is supplied from the compressor at around 450°C thus has to be further heated before entering the SOFC cathode in order to keep a sufficiently high operating temperature. This is achieved by using a first portion of flue gas heat from the gas turbine. The gas turbine outlet temperature is selected fairly high to achieve a high enough air pre-heating temperature. Alternatively the last part of the temperature increase of the inlet air could be achieved using for example product gas heat, however, this would lead to a more complex heat exchanger arrangement. The second portion of the flue gas heat is transferred to the feed water of the steam cycle in an economizer. Furthermore also residual heat from the transport gas and product gas export is used in this section. Due to its straight forward arrangement the steam cycle condenser is not shown in the figure.

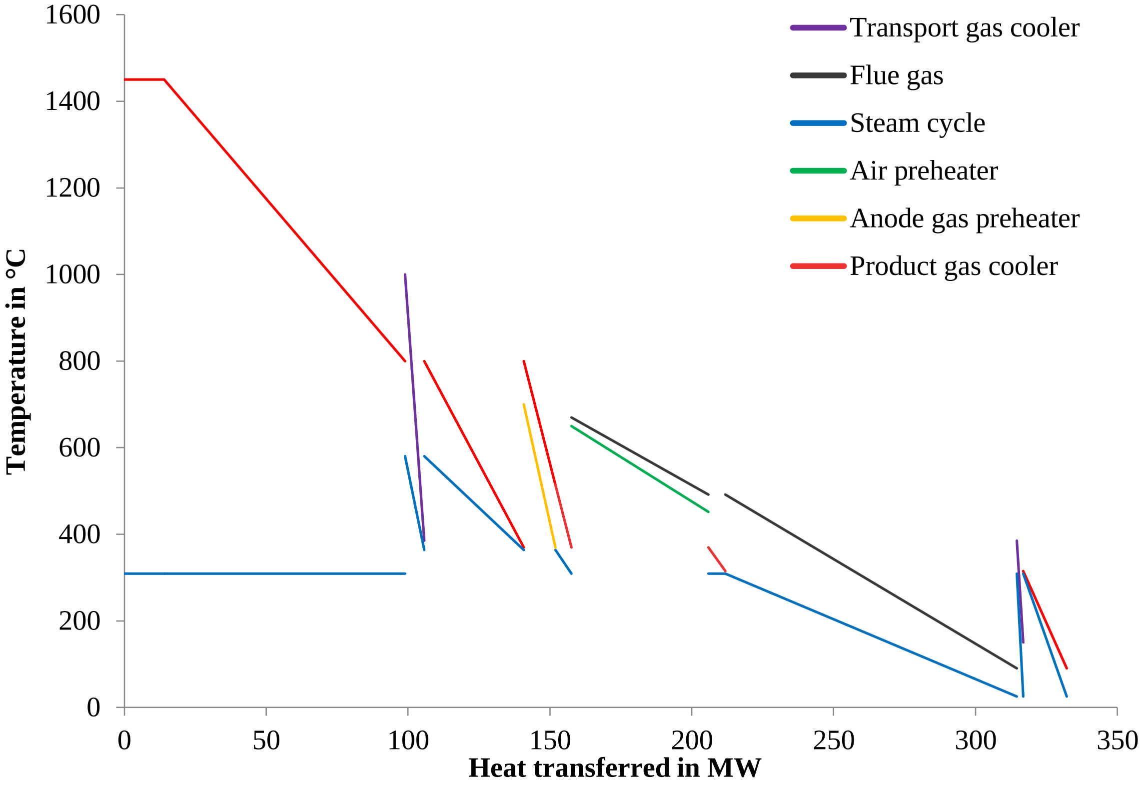

Figure 2: Q-T diagram of optimized system heat integration (syngas split fraction 0.6, see below)

4.2 Parameter studies

Besides the optimized heat integration in the proposed system two parameters have a major impact on the performance. The first one of these is the split fraction of syngas that is extracted from the system as opposed to being sent to the SOFC. Extracted syngas may be used for various purposes, such as chemical synthesis, energetic utilization and others. For simplicity and comparison to existing concepts in the following two different utilization options are considered. Either the syngas is directly converted to electricity in a reference combined cycle power plant (rCC)at a nominal efficiency of 60% (LHV), or it is converted to methane for transportation in a natural gas infrastructure in order to be converted in an rCC later.

As a reference point first of all the split fraction is set to 1. At this operating point syngas is generated in the gasifier, cleaned and completely sent to the reference combined cycle, while excess heat, such as from cooling the gasifier, is used in the steam cycle. This means no fuel is sent to the SOFC and conversely no anode exhaust is sent to the gasifier, instead the conventional gas feeds are used. In this arrangement the gasifier produces 858.5MW (LHV) of syngas from 1052.0MW (LHV) of coal and 56.67MW of work is generated in the steam cycle while 42.3MW are consumed in the air separation plant, which overall leads to a total electrical net efficiency of 50.3% if full syngas conversion in the rCC is assumed. This is value is very similar to data available in the literature for non CO_2-capture IGCC [1,2,6].

If now the split fraction is step-wise reduced, which means more and more syngas is converted in the system itself (SOFC, gas turbine and steam cycle), one can see from Figure 3 that electrical output increases while the chemical output of the system decreases. At the same time the global electrical efficiency, which also considers the conversion of the extracted syngas in the rCC rises from the inital 50.3% up to 62.8% at a split fraction of 0.

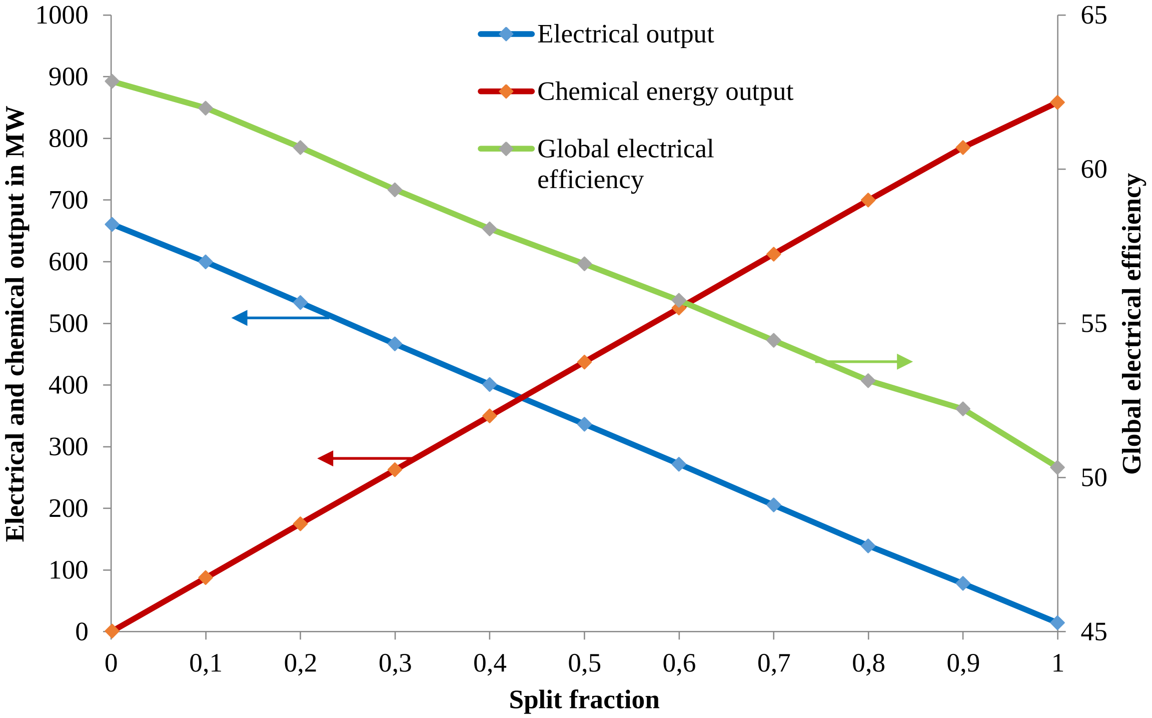

Figure 3: Electrical and chemical output in dependence of the syngas split fraction.

Figure 4 shows an equivalent diagram as Figure 3 but for a system with additional methanation. As mentioned this allows transportation of the resulting methane in any natural gas grid and might be well suited to indirectly flexibilize the usually very inflexible IGCC. Conclusively, the additional conversion step reduces the achievable chemical output compared to the system without methanation, and increases the internal electrical output because more heat is available for the steam cycle. However, the global electrical efficiency, when considering the rCC, is lower especially for high split fraction where only a global efficiency of 45.3% is achieved. The significance reduces with lower split fractions, since less syngas is methanized until it finally also converges to the 62.8% electrical efficiency at split fraction 0.

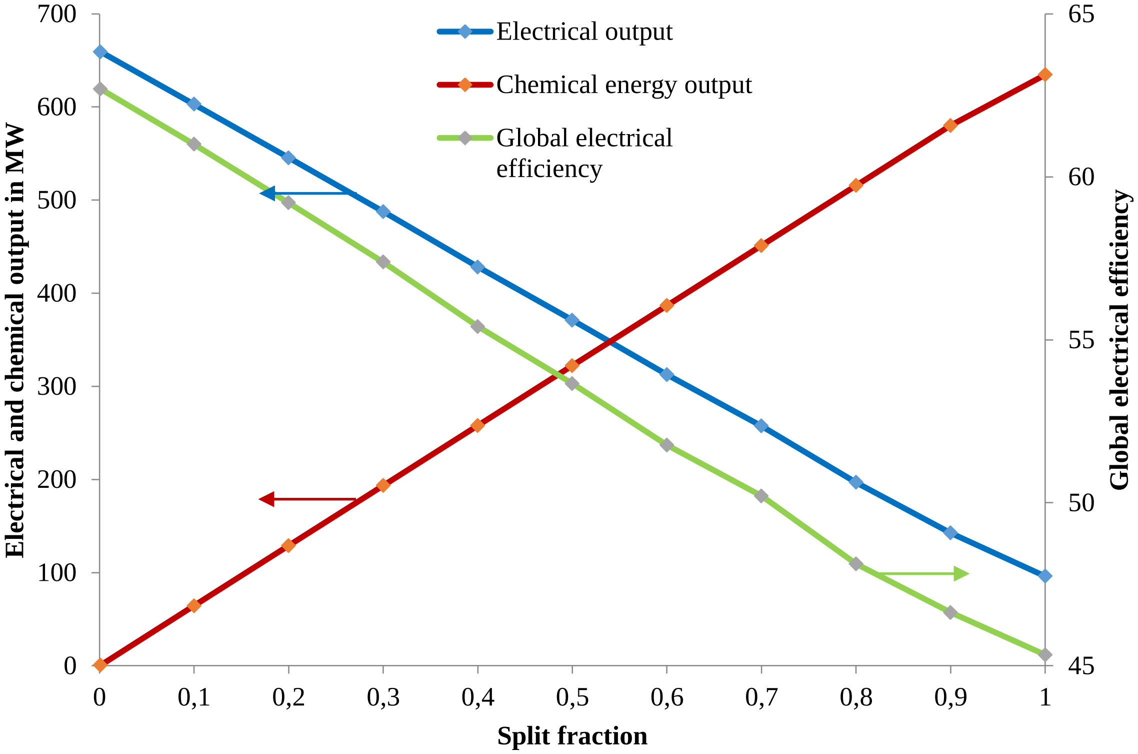

Figure 4: Electrical and chemical output in dependence of the syngas split fraction with methanation.

The second important parameter is the split fraction of the anode exhaust recirculated to the gasifier. Despite that theoretically the anode exhaust could be completely recirculated to the gasifier it has been found this does only make sense to a certain extend. On the one hand some gases like CO_2 and H_2O, which are mainly present in the anode exhaust, have to be added to the gasifier anyway to serve as transport and purge gas, as well as gasification agent. Furthermore, if residual fuel is recirculated exergy destruction in the post combustion is avoided. However, on the other hand , in conjunction with the high temperature entrained flow gasifier it is obvious that any additional gas has to be heated to the gasifier temperature and thus requires energy that has to be delivered from the fuel and oxygen. Thus, an optimum for recirculation of anode exhaust has been found at a mass flow of 15kg/s, which is similar compared to the supply gas flows of a conventional arrangement. A comparison of the syngas composition without and with recirculation is shown in Table 2. As can be seen the gas composition is quite similar, with an increased amount of H_2O, CO and CO_2 and slightly decreased H_2. Furthermore a certain accumulation of other inert gases such as N_2 and Ar can be observed, which is to be expected. Due to the limited amount of anode exhaust, which can be reasonably recirculated the effect of the recirculation approach is limited to an increase in the cold gas efficiency from originally 82.1% to 83.2%. However, since in the integrated system also the heat extracted from the gasifier is used in the steam cycle the overall effect of the recirculation can not only be determined by the cold gas efficiency. To further investigate the impact of the recirculation on the electrical efficiency Figure 5 shows the absolute efficiency gain achieved at different split fractions. As can be seen the initial step from split fraction 1 to 0.9 exhibits a larger absolute efficiency gain than for any other steps. This can be attributed to the effect of the exhaust recirculation.

Table 2: Comparison of the syngas without and with anode exhaust recirculation.

	Original	Recirculation	Change
	Mass flow in kg/s		in %
H_2	1.68	1.54	-8.19
H_2O	2.57	2.96	15.13
N_2	0.68	0.77	13.74
CO	65.24	67.95	4.16
CO_2	5.04	6.57	30.37
Ar	0.79	0.89	13.05
CH_4	0.01	0.00	-84.36
H_2S	0.21	0.23	12.04
Trace	0.05	0.06	23.93
Total	76.26	80.98	6.19

A further quantification of the impact might be drawn from the second plot in Figure 5, which shows the gain in efficiency divided by the share of overall fuel input that is supplied as SOFC AC power output. This quantity indirectly measures the amount of exergy efficiency added to the system by the fuel cell, while the internal electrical efficiency of the SOFC stays almost constant at about 47.8% (LHV). For example at a split fraction of 0.9 a share of 2.8% of the fuel input (29.3MW out of 1052.0MW) is converted to electricity in the fuel cell, while the global system efficiency rises by 1.9% from 50.3 to 52.2% (an increase of 20.0MW).

Any further 0.1 step decrease in the split fraction only leads to an efficiency gain of on average 1.1%. Thus due to the recirculation the first 29.3MW of SOFC accounts for an additional efficiency gain of 68% of its nominal electricity production share, while any additional installation of SOFC has less impact.

This is important with regards to the economic viability of SOFC installations since to date SOFC are still very expensive and thus it is not economical to install large quantities of SOFC. However, as has been shown a small amount of SOFC installation can bring an over-proportional benefit to the IGCC system, which might make a hybrid IGCC configuration with small SOFC more economically viable.

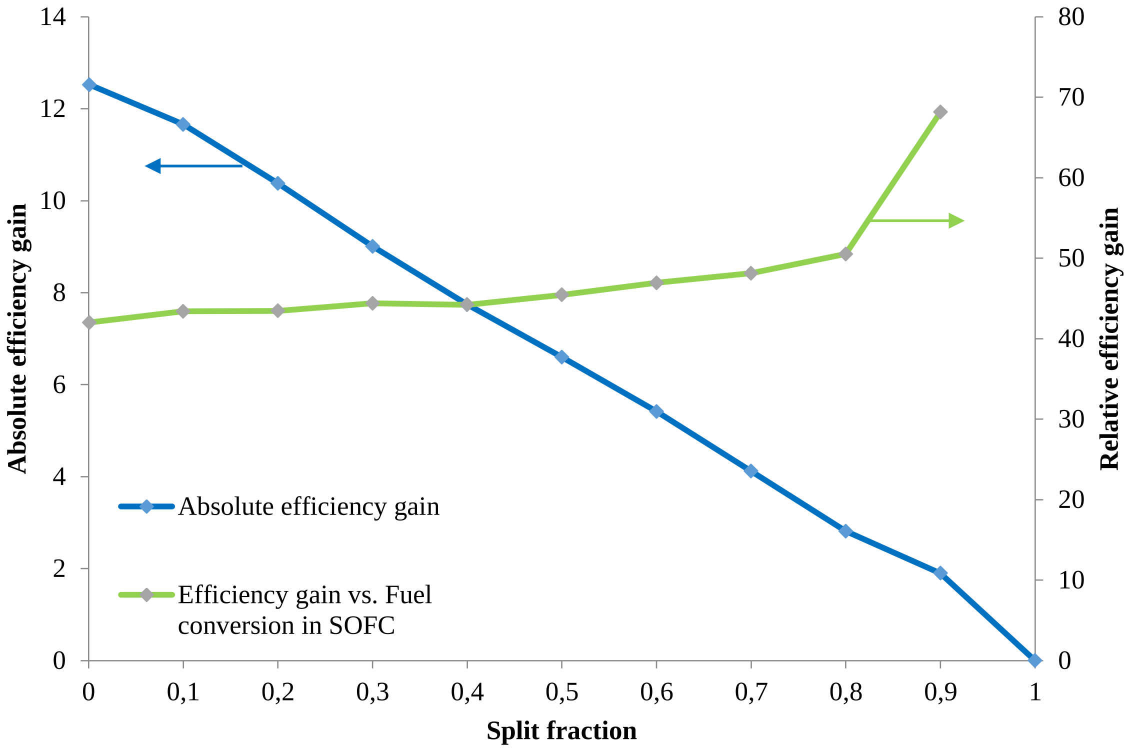

Figure 5: Comparison of absolute and relative efficiency gain impact of the fuel cell at different anode exhaust split fractions.

5 SUMMARY AND CONCLUSION

A novel gasification concept combining entrained flow gasification of coal and Solid Oxide Fuel Cells (SOFC) has been developed and evaluated. The main advantage of the concept is a recirculation of anode exhaust from the SOFC to the gasifier in order to substitute transport gas and gasification agent. At the same time a share of the unconverted fuel and heat from the anode outlet is chemically recycled and thus the cold gas efficiency of the gasifier is found to increase from 82.1% to 83.2%. However, the impact of this approach has been found to be limited due to the fact that too high flows of additional gas lead to a decrease in efficiency because of rising heat duty. The maximum electrical efficiency achieved in the coupled system reaches up to 62.8% when no syngas is extracted for further purposes. As to be expected this is similar to values achieved in prior works for comparable integrated entrained flow gasification and pressurized SOFC systems [6]. Furthermore an indirect flexibilization option is proposed using methanation of a share of the syngas to make it transportable and time shift electricity production, which is associated with an efficiency penalty of up to 5% depending on the share of syngas which is methanized.

Future work will comprise further thermodynamic and economic assessment of the impact of different split fractions on hybrid IGCC SOFC power plants and integration of carbon capture. Furthermore experimental validation of the results of this study is necessary.

6 ACKNOWLEDGEMENTS

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