Understanding the inefficiencies of an IGCC concept with carbon capture based on an advanced exergy analysis

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Abstract:

The generation of electricity from coal results in the emission of CO_2 to the environment, which can almost be omitted by using carbon capture. Integrated gasification combined-cycle (IGCC) power plants with carbon capture are commercially available and offer a high overall net efficiency compared to other technologies. The major components of the analyzed IGCC concept are an oxygen-blown Shell gasifier, a gas quench, and a Selexol® unit for H_2S and CO_2 separation. The evaluation of the IGCC concept is first performed using a conventional exergy analysis. It is shown that the gasification process and the combustion of syngas in the gas turbine have the highest shares in exergy destruction. However, the real potential of improvement is generally much lower due to the necessity of chemical reactions and the limitation of temperatures by materials. Based on the findings of the conventional exergy analysis, an advanced exergy analysis is conducted subsequently. The framework is used to identify the interdependencies among the system components and the real improvement potential of the overall system. It was found that the gasifier, gas turbine system and syngas cooler are the most promising components for improvement even though the percentages of the overall avoidable exergy destructions are small. Additionally, the exergy destructions in many components are strongly affected by the exergy destructions within other components due to the highly interdependent design. Particularly, the interdependency between gasification and combustion is very strong.

Keywords:

Advanced Energy Systems, Electricity Generation, IGCC, Exergy Analysis, Advanced Exergy Analysis

1 Introduction

Projections from the IEA concerning the worldwide primary energy usage show an increasing demand throughout the forthcoming years [1]. While the relative consumption of oil is going to decline in the period between the years 2000 and 2050, the coal and gas consumption likely increases [2] due to secured vast resources and global availability. The projections also point out that coal is going to be the world's primary source of energy by the year 2050, especially regarding power generation.

Considering an increased industrial competition and stricter governmental regulations worldwide, huge efforts for the development of new, efficient and economically competitive processes with a low emission of pollutants are necessary [3, 4]. This particularly applies to coal technologies.

With respect to efficiency and pollutant capture, the integrated gasification combined-cycle (IGCC) technology is a promising concept. In general, studies show that the IGCC concept is preferable to conventional pulverized coal (PC) steam power plants when carbon dioxide (CO_2) capture is used [5].

The two major components of an IGCC plant, gasifier and gas turbine, are recognized today as state-of-the-art [6]. Moreover, experience from various IGCC demonstration plants built in the last 40 years is also available [7, 8]. Nevertheless, many issues must still be resolved concerning the technology and availability of plants employing IGCC technology [7, 9]. Due to these problems and currently low electricity prices only some IGCC plants producing electricity have shown cost-efficient operation to date while some other plants have already been shut down. Additionally, some prospective projects for plant construction are halted or delayed due to unfavorable market conditions [8] as preliminary cost estimates show that IGCC capital costs are 15-20 % higher compared to a similar PC plant [7].

As the IGCC technology and design are still under development, there is a considerable variety of possible plant layouts. In order to determine the best layout and technology from a thermodynamic perspective, the exergy concept [10] can successfully drive the design synthesis process. An advanced exergy analysis [11] offers additional information about the thermodynamic interactions between the components and the real optimization potential of such highly integrated plants, affecting both thermodynamic efficiency and economic feasibility.

The considered plant layout is a high-efficient IGCC concept with carbon capture [12] using a Shell gasifier and an H-class gas turbine concept representing a feasible near future solution [5]. By analyzing the proposed plant concept, the present paper focuses on the identification of interdependencies regarding exergy destruction and the concept's real improvement potential. This is particularly important regarding future optimization approaches.

2 Methodology

Exergy analysis is a convenient and powerful tool to analyze thermal process systems. Possible options for process improvement are derived by identifying and evaluating the thermodynamic inefficiencies of the system.

2.1 Exergy Analysis

To analyze the efficiency of a power or chemical process from a thermodynamically unbiased point of view, the exergy concept has proven to be advantageous with its methodology and capabilities being well established [10, 13, 14]. Exergy is thereby an integral measure to account for both the quantity and quality of energy. The ambient conditions are set to 15 °C and 1.013 bar whereas the Szargut-model [13] is used for chemical exergy calculations.

Under steady state conditions, the exergy destruction rate $\dot{E}_{D,k}$ within the k-th component is calculated as the difference between the exergy rate of fuel $\dot{E}_{F,k}$ and the exergy rate of product $\dot{E}_{P,k}$ [10].

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} \tag{1}$$

To assign the exergy rates of fuel $\dot{E}_{F,k}$ and product $\dot{E}_{P,k}$ the SPECO approach [15] is used. The exergy destruction $\dot{E}_{D,k}$ thereby quantifies the thermodynamic irreversibilities occurring within the component in regard. The main causes are related to chemical reactions, heat transfer, fluid friction and mixing of streams at different temperature, pressure and composition [10]. It is further used to calculate the exergetic efficiency ϵ_k of the k-th component.

$$\epsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \tag{2}$$

The exergetic efficiency is the only measure to unambiguously determine the thermodynamic performance of a component [11]. Additionally, the exergy destruction ratio $y_{D,k}$ is used to identify the contribution of each component to the reduction of the overall system's exergetic efficiency.

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}} \tag{3}$$

The application of an exergy analysis provides information which is not available through a conventional thermodynamic analysis. Thereby, possible means to improve the system are easily derived. In contrast, it is yet not known whether the modifications proposed by a conventional exergetic evaluation lead to an improved overall system [11] as no implications caused by the structure are taken into account for the system. Moreover, the real available improvement potential is unknown. These issues can be resolved by conducting an advanced exergy analysis.

2.2 Advanced Exergy Analysis

The advanced exergy analysis concept [16] provides the framework for the identification of the thermodynamic interactions of each system component as well as their real improvement potentials. This is achieved by splitting the exergy destruction within each component into its endogenous and exogenous parts as well as its avoidable and unavoidable parts, respectively.

In order to derive the thermodynamic interdependencies among the system components, the exergy destruction of each component is split into its endogenous and exogenous parts.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX} \tag{4}$$

The endogenous exergy destruction $\dot{E}_{D,k}^{EN}$ is the remaining irreversibility of the k-th component when it operates with the same exergetic efficiency ϵ_k and all the remaining components operate in an ideal way [11]. In contrast, the exogenous exergy destruction $\dot{E}_{D,k}^{EX}$ is defined as the part of the exergy destruction occurring within the k-th component due to the irreversibilities of other components.

For the calculation of the endogenous exergy destruction several approaches [17–19] have been suggested. However, the different methods are still tedious to use, if applied to complex systems, and face theoretical shortcomings [17, 18] and computational problems for chemical reactions [19]. Therefore a new concept for the calculation of the interactions among components was developed and is used here for analyzing the IGCC concept.

The new concept [20] uses an aggregated superstructure model [21] in combination with inherent features of the exergy concept. In contrast to previous approaches, all mass and energy balances are fulfilled. By employing the new straightforward approach, the computational load is highly reduced.

To complement the determination of component interdependencies, the achievable improvement potential is determined for each component. Therefore, the exergy destruction is split into its unavoidable and avoidable parts.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{UN} + \dot{E}_{D,k}^{AV} \tag{5}$$

By calculating the unavoidable exergy destruction $\dot{E}_{D,k}^{UN}$, it is possible to determine the part of the exergy destruction that cannot be further reduced. These constraints are set by techno-economic limitations such as availability, cost of materials as well as manufacturing methods. This enables engineers to use knowledge, experience, and expectations to identify and quantify potential changes in design and operation for the component in regard. Meanwhile, The avoidable exergy destruction $\dot{E}_{D,k}^{AV}$ represents the potential savings in exergy destruction.

An interesting feature of the advanced exergy concept is the combination of both splittings of exergy destruction. In order to determine the most promising modifications, the values of endogenous avoidable and exogenous avoidable exergy destruction determine the priorities for improving the overall system.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{UN,EN} + \dot{E}_{D,k}^{UN,EX} + \dot{E}_{D,k}^{AV,EN} + \dot{E}_{D,k}^{AV,EX} \tag{6}$$

$$\dot{E}_{D,k}^{AV,EN} = \dot{E}_{D,k}^{EN} - \dot{E}_{D,k}^{UN,EN} \tag{7}$$

$$\dot{E}_{D,k}^{AV,EX} = \dot{E}_{D,k}^{AV} - \dot{E}_{D,k}^{AV,EN} \tag{8}$$

The simultaneous consideration of the different parts of exergy destruction identifies the real potential for improving the particular component and the overall system based on simple rules [16].

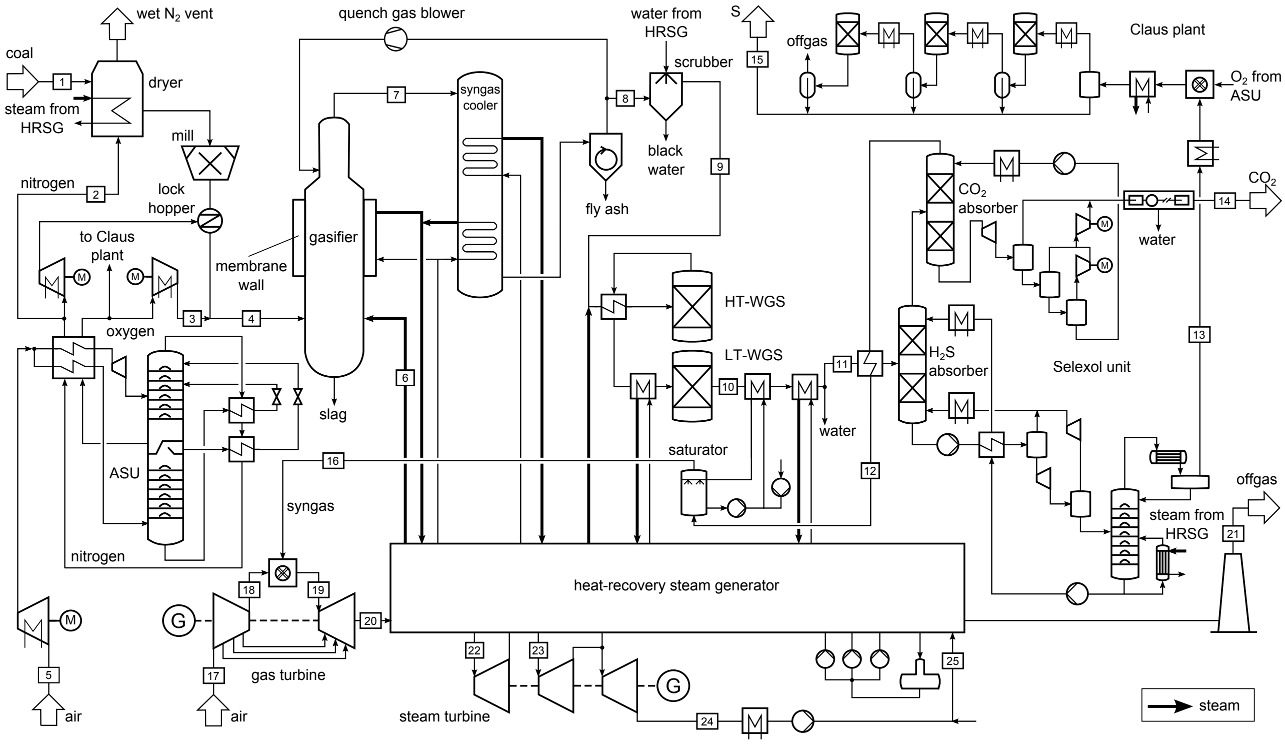

Fig. 1. Flowsheet of the analyzed IGCC concept [12].

To improve understanding of the degree of interdependencies among the components, the exogenous exergy destruction of the k-th component is further split to account for binary component interactions [18].

$$\dot{E}_{D,k}^{EX} = \sum_{r \neq k}^{n} \dot{E}_{D,k}^{EX,r} + \dot{E}_{D,k}^{mexo} \tag{9}$$

The remaining difference $\dot{E}_{D,k}^{mexo}$ represents the simultaneous interactions among all other components together and is called the mexogenous exergy destruction. A large value of the mexogenous exergy destruction is an indicator for potentially strong component interactions in highly integrated systems. Therefore, it permits the identification of the real importance of components by calculating the sum of the avoidable exergy destruction. Characterizing the importance of component k from the thermodynamic point of view, the components with the largest values of $\dot{E}_{D,k}^{AV,\Sigma}$ should be given the priority for improvement.

$$\dot{E}_{D,k}^{AV,\Sigma} = \dot{E}_{D,k}^{AV,EN} + \sum_{r \neq k}^{n} \dot{E}_{D,k}^{AV,EX,r} \tag{10}$$

The results from the advanced exergy concept provide the system designer and operator with information that cannot be derived from any other method available.

3 System Description

The IGCC concept analyzed in this study is mainly derived from the plant configuration considered for power generation with carbon capture by the U.S. DOE [5]. The concept is further described in detail as a high-efficiency base case by Sorgenfrei and Tsatsaronis [12] with its flowsheet being shown in Fig. 1. Some parameters of the process were slightly modified. Stream data and parameters of selected streams are presented in Table 1. The major assumptions used for the simulation in Aspen Plus® are given in Table 2.

Table 1. Stream parameters for selected flows of the studied IGCC concept.

No.	Type	Temperature [°C]	Pressure [bar]	Mass flow [kg/s]	Exergy rate [MW]
1	Coal	15.0	1.013	80.0	2557.5
2	Nitrogen	18.0	1.100	175.0	5.7
3	Oxygen	120.6	45.000	60.3	24.9
4	Coal only	50.0	1.013	76.2	2557.5
5	Air	15.0	1.013	257.8	1.5
6	Steam	400.0	45.000	6.8	9.0
7	Raw gas	900.0	40.000	301.4	3888.7
8	Raw gas	280.0	39.310	139.9	1713.7
9	Raw gas	141.4	38.966	154.2	1711.6
10	Shift gas	281.0	38.766	249.2	1718.5
11	Shift gas	29.4	34.896	207.3	1648.8
12	Clean gas	20.0	34.626	25.7	1480.0
13	Acid gas	48.0	1.600	2.0	18.1
14	CO_2	45.0	110.000	170.3	163.6
15	Sulfur	150.0	1.100	0.6	11.8
16	Syngas	145.1	34.126	42.0	1493.7
17	Air	15.0	1.013	1230.0	7.3
18	Air	432.8	19.200	957.8	401.3
19	Combustion gas	1490.0	17.952	999.8	1555.0
20	Exhaust gas	612.9	1.050	1272.0	451.3
21	Offgas	133.0	1.013	1272.0	69.7
22	Steam	590.0	164.000	196.1	332.5
23	Steam	562.0	42.000	213.1	330.3
24	Condensate	26.7	0.035	245.8	32.9
25	Water	22.0	2.041	368.6	18.6

As depicted in the flowsheet, the IGCC concept consists of five major subsystems, these being the gasifier, the air separation unit (ASU), a complete acid gas removal (AGR) train with CO_2 capture and a Claus plant, as well as a combined-cycle including a gas turbine (GT) system and an accompanying steam cycle supplied by a heat-recovery steam generator (HRSG). The concept represents a high-efficient and highly integrated design.

The major component is a Shell-type gasifier that converts dry bituminous coal to synthesis gas (syngas) using intermediate-pressure (IP) steam. The coal composition based on an as-received mass basis is 64.61 % C, 4.39 % H, 1.39 % N, 0.86 % S, 7.05 % O, 12.2 % ash and 9.5 % moisture (Illinois No.6). First, the wet coal is dried by heated nitrogen vented from the ASU, then it is crushed in a bowl mill and afterwards fed pneumatically to the gasifier. Furthermore, the ASU supplies 98 % (mole) oxygen for the gasification and the Claus plant operation. The gasifier itself is an oxygen-blown, entrained-flow gasifier of the Shell-type with high carbon conversion rates above 99 %. The operating temperature and pressure are 1550 °C and 40 bar, respectively. The syngas is first quenched by a gas recycle before entering the syngas cooler generating saturated steam at intermediate and high-pressure (HP). Subsequently, particulates are removed by a cyclone, candle filters and a venturi scrubber.

The raw syngas is then shifted in a two-stage water gas shift reactor (WGS) with intermediate cooling in sour shift. Hence, the hydrogen (H_2) output is maximized whereas at the same time carbonyl sulfide (COS) is hydrolyzed to hydrogen sulfide (H_2S). At the outlet of the low-temperature WGS reactor (LT-WGS) the carbon monoxide (CO) concentration is 1.9 % (mole). Subsequently, the syngas is cooled before entering the AGR unit.

The AGR unit uses a Selexol® based process. Within the first absorption column H_2S is removed by physical absorption. The solvent is subsequently regenerated in a corresponding desorption column using low-pressure (LP) steam. The concentrated sour gas is then further processed via a Claus plant to elemental sulfur. After the H_2S removal, the syngas enters the CO_2 absorber, reducing the CO_2 mole fraction to 0.007 % (mole) in the clean gas. Using a three-stage flash, the CO_2 is then desorbed from

Table 2. Overview of major assumptions made for modeling the IGCC concept in Aspen Plus®.

System/Component		Value
General		
Ambient temperature	°C	15
Ambient pressure	bar	1.013
Mechanical efficiency	%	99
Electric motor efficiency	%	95
CO_2 comp. isentropic stage eff.	%	77.4-78.7
CO_2 exit temperature	°C	45
CO_2 exit pressure	bar	110
Air, N_2 and O_2 comp. isentropic eff.	%	85
Gasification island		
Coal dryer-residual moisture	%	5
Coal mill-electrical demand	kJ/kg	36
Steam/coal mass ratio	–	0.09
Oxygen/coal mass ratio	–	0.78
Nitrogen/coal mass ratio	–	0.09
O_2 pressure to gasifier	bar	45
N_2 pressure to gasifier	bar	56
Carbon conversion efficiency gasifier	%	99.7
Heat loss gasifier ($HHV_{coal,ar}$)	%	0.5
Steam production gasifier ($LHV_{coal,ar}$)	%	1.5
Gasifier temperature	°C	1550
Gas quench temperature	°C	900
Quench gas blower isentropic eff.	%	78
O_2 mole purity	%	98
Outlet pressure HP/LP column	bar	5.8/1.3
Outlet temperature of N_2,O_2	°C	18
AGR unit		
Gas temperature at inlet	°C	30
LP steam production per kg of H_2S	MJ/kg	29.5
Solvent pumps isentropic eff.	%	85–75
Solvent/gas mole ratio H_2S absorber	–	0.17
Solvent/gas mole ratio CO_2 absorber	–	1.05
Refrigeration comp. isentropic eff.	%	78
Gas turbine system		
Firing temperature	°C	1490
Pressure ratio	–	19.5
Compressor polytropic efficiency	%	91.5
Rotor isentropic stage eff.	%	90.5–92
Exit pressure	bar	1.05
Steam cycle		
Steam turbine polytropic eff.	%	HP 90
	%	IP 92
	%	LP 87
Condenser pressure	bar	0.035
Minimal temperature differences		
Gas/gas	K	20
Gas/liquid	K	10
Liquid/liquid	K	5
Pressure losses		
Pressure loss liquid/gas per 100 K	%	2/3
Pressure loss evaporation	%	5

the rich solvent and is further treated for transport. The loading capacity of the lean solvent is increased before entering both columns by cooling to -1 °C by using an air cooling and a CO_2 refrigeration process.

The H_2 fraction of the syngas leaving the AGR units amounts to 92.1 % (mole). Such high hydrogen concentrations cannot be processed by the GT combustor without dilution. Instead of using pressurized air, the syngas is diluted by hot water in a saturator. After appropriate conditioning, the syngas is fired in the GT system. The GT model [22] is based on the Siemens SGT5-8000H frame. According to the ISO 2314 standard, the turbine inlet temperature (TIT) of the gas turbine running on syngas, increases slightly by 4 K while the efficiencies of the compressor and turbine remain the same. Furthermore, the demands for cooling and sealing air change insignificantly and still account to 20.4 % of the GT compressor's inlet air flow.

The flue gas exiting the GT system enters the HRSG at 615 °C. Steam is generated at three pressure levels with a single reheat by cooling the flue gas to 133 °C. The steam parameters at the turbine inlets are 590 °C/164 bar for the HP, 562 °C/42 bar for the IP and 202 °C/3 bar for the LP steam turbines, respectively. Furthermore, the HRSG is highly integrated into the overall system. It provides superheated IP steam for the gasification and shift processes. Additionally, preheated IP water is produced for the particulate scrubber. Within the syngas cooler and the high-temperature WGS (HT-WGS) unit, saturated HP steam is generated. Furthermore, saturated IP steam is generated within the gasifier and the syngas cooler. The LT-WGS unit is used to preheat the overall water stream entering the HRSG. Heat is supplied by the HRSG to the coal dryer and the desorption columns of the AGR unit.

Concerning the overall plant design, the gas turbine system provides 62 % of the gross electricity production. The overall net efficiency results to 37.9 % based on the lower heating value (LHV_{ar}) of coal.

Table 3. *Results from the conventional exergy analysis for the subsystems of the IGCC concept.*

Subsystem	$\dot{E}_D$ [MW]	y_D [%]	$\dot{E}_L$ [MW]
Gasification island	857.1	34.35	26.8
Gas turbine system	446.4	17.70	9.0
Steam cycle	88.1	8.35	126.9
AGR unit	75.9	2.95	0.0
ASU	34.9	1.38	0.5
CO_2 compressor	19.2	0.75	163.6
Total	1521.7	65.47	326.8

4 Results

The conventional and advanced exergetic analyses are used for the identification of thermodynamic improvement potentials of the IGCC concept. First, an analysis based on aggregated subsystems is used to identify the most important components. Using these results, a detailed conventional exergy analysis is conducted and the top ten components ordered in descending order of their exergy destruction are presented. Furthermore, these components are analyzed employing the advanced exergy analysis approach for the identification of the subsystem's interdependencies. Based on an estimation of potential modifications in the operation of the currently employed technology, the potential for improvement concerning these components is discussed.

4.1 Conventional Exergy Analysis

A general overview of the distribution of exergy destructions and exergy losses among the different subsystems of the IGCC concept is developed in the beginning. The values are presented in Table 3 showing the dominating subsystems in terms of exergy destruction.

The dominant roles of the gasification island and the gas turbine system are shown clearly as these subsystems have the highest shares in exergy destruction. This results from the highly irreversible chemical reactions, particularly in the gasifier and the GT combustion chamber. Moreover, the gasification island represents a complex system due to its units for coal drying, preparation of the gasification agents, coal gasification and preparation of the syngas.

The steam cycle and the AGR unit also show a significant share in exergy destruction. However, the steam cycle does not include any heat transfer outside of the HRSG. These four subsystems are highly important to the overall plant. Therefore, they are disaggregated into smaller units to obtain more details about the sources of thermodynamic inefficiencies. In contrast, the ASU and the CO_2 compressor are not further discussed here. The prepared CO_2 stream leaving the overall system represents the largest exergy loss due to its high chemical exergy. Another large exergy loss is represented by the offgas leaving the HRSG. The exit temperature is calculated to about 132 °C since a lot of low-temperature heat is already transferred to the steam cycle by the LT-WGS unit.

Based on a more detailed exergy analysis, the ten components with the highest exergy destruction in the overall plant are presented in Table 4 among other values discussed in the context of the advanced exergy analysis. Furthermore, the exergy destruction ratios of these units are depicted in Fig. 2. The gasifier and the GT combustion chamber have the highest shares in exergy destruction.

Another category identified is represented by the exergy destructions caused by heat transfer within the WGS unit and the syngas cooler. In addition, the WGS unit includes the injection of steam. The gas quench is calculated to position nine since the gas composition does not change. However, the temperature difference is about 1260 K. Compared to an ISO-model with only three model components, the detailed GT model in this study shows that some exergy destruction has shifted from the GT

Table 4. Results of the conventional and advanced exergetic analyses for the ten components with the highest exergy destruction in the IGCC concept.

No.	Component	$\dot{E}_D$ [MW]	y_D [%]	ϵ [%]	$\dot{E}_D^{UN}$ [MW]	$\dot{E}_D^{AV}$ [MW]	$\dot{E}_D^{EN}$ [MW]	$\dot{E}_D^{EX}$ [MW]	$\dot{E}_D^{AV,EN}$ [MW]	$\dot{E}_D^{AV,EX}$ [MW]
1	Gasifier	644.9	25.06	75.01	569.7	75.1	311.2	333.7	34.0	41.2
2	GT comb. chamber	340.3	13.22	76.01	295.3	44.4	139.7	200.6	18.2	26.2
3	WGS unit	85.9	3.34	91.98	81.1	4.7	31.1	54.7	1.7	3.0
4	GT turbine	77.6	3.02	93.51	63.3	14.3	28.0	49.6	5.2	9.1
5	Syngas cooler	60.1	2.34	69.44	39.6	20.5	21.5	38.6	7.3	13.2
6	H_2S capture cycle	35.7	1.39	–	35.2	0.5	14.3	21.5	0.2	0.3
7	CO_2 capture cycle	35.1	1.37	–	33.1	2.1	13.1	22.0	0.8	1.3
8	GT compressor	27.2	1.06	94.71	21.0	6.3	9.6	17.6	2.2	4.1
9	Gas quench	24.2	0.94	–	24.2	0.0	8.5	15.7	0.0	0.0
10	Condenser	20.5	0.80	–	20.5	0.0	7.2	13.3	0.0	0.0

$\dot{E}_{F,tot} = 2573.4\,\text{MW}$

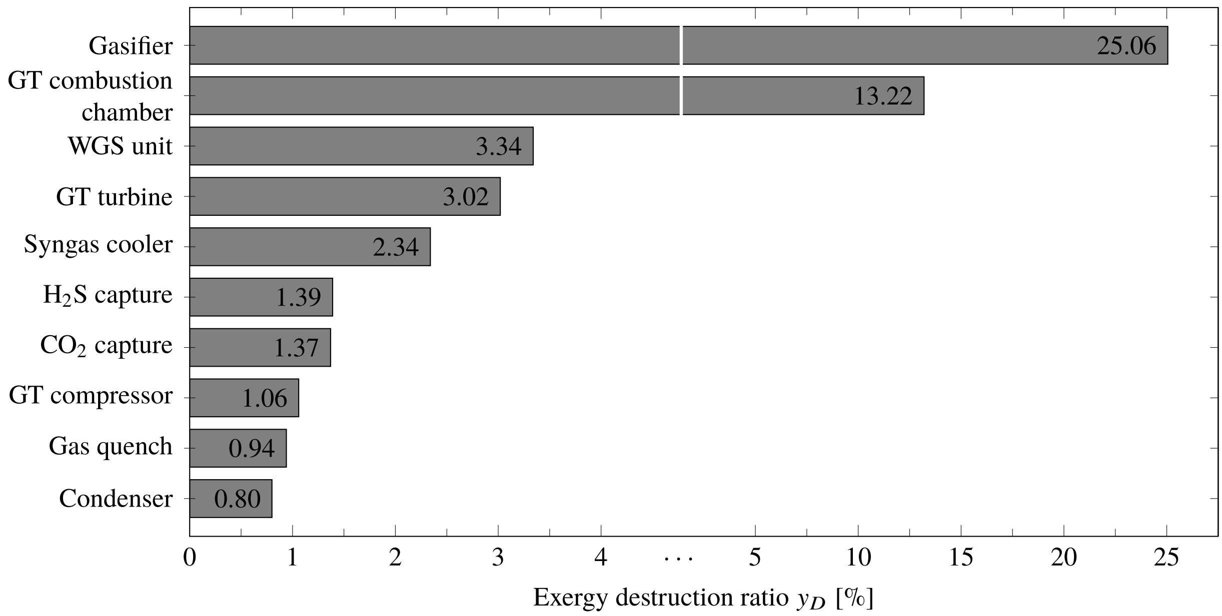

Fig. 2. Detailed results of the conventional exergy analysis.

combustion chamber to the turbine section. Within the GT turbine, irreversibilities are caused by mixing of the cooling and sealing air into the main gas stream, blade and vane cooling, and friction of the main gas stream. When splitting the AGR unit into its subunits, the H_2S and CO_2 capture cycles obtain the ranks six and seven among all components of the overall system. The H_2S capture cycle has a significant demand for electricity and cooling due to the low operating temperature. The CO_2 capture cycle needs electricity and CO_2 gets desorbed in a three-stage flash process causing exergy destruction. The GT compressor is associated with high exergy destruction due to the large airflow needed for diluting the syngas in the GT combustion chamber.

Splitting the steam cycle into its components reveals that approximately half of the exergy destruction is caused by the heat transfer within the HRSG. The steam turbine, which generates 38 % of the gross electricity output, causes approximately a fourth of this exergy destruction, although the assumed polytropic efficiencies are high. Another fourth belongs to the condenser. Finally, the exergy destruction within the condenser is determined by constraints given by the cooling water supply.

An interesting observation can be made for the exergetic efficiencies of the different units. Being a high-efficient design, most of the units exhibit high exergetic efficiencies. The smaller values of the gasifier and the combustion chamber result from the irreversible chemical reactions. In addition, heat transfer limitations and design considerations decrease the efficiency in the case of the syngas cooler. For the AGR capture units, the gas quench and the condenser, no attempt was made to define an exergetic efficiency as these units are merely dissipative processes. The results obtained by the conventional analysis suggest that the high exergy destructions within the gasifier, GT combustion chamber and the following WGS unit, GT turbine and syngas cooler make them the most important units for further improvement of the overall system.

4.2 Advanced Exergy Analysis

Using the conventional exergy analysis as a starting point for further investigations, the advanced exergy analyses were conducted to provide a deeper understanding of the IGCC concept.

4.2.1 Unavoidable and Avoidable Exergy Destruction

By considering the best working conditions for the studied components, the exergy destruction decreases by approaching the technical and economic constraints present. Even though the assumptions made are subjective, general trends can be identified. In general, a conservative approach was used here.

For the gasifier, the operating temperature decreases by 100 K mainly based on a reduced oxygen and steam demand. Moreover, the temperature is affected by a higher temperature and lower pressure of the gasification agents as well as a slightly decreased nitrogen flow entering through the lock hopper. The syngas cooler and the WGS unit are assumed to produce superheated steam instead of saturated steam. The units produce HP steam as much as possible and the pressure drop is decreased. Likewise, the minimum temperature difference between the raw gas and water is reduced and the evaporation pressure of water is increased accordingly.

Within the GT system, the firing temperature of the GT combustion chamber increases by 200 K based on reducing the stoichiometric oxygen ratio, whereas the pressure drop is slightly reduced and the radiation heat loss is omitted. Moreover, the isentropic efficiencies of the GT compressor and turbine are slightly increased. Within the GT turbine, the temperatures downstream of mixing the cooling and sealing air into the main gas stream remain constant. Based on this approach, the airflows are adjusted. It is further assumed that the exhaust temperature remains constant. Unavoidable conditions for both capture cycles are expected to feature higher isentropic efficiencies for compression and expansion, lower pressure drops of the column and smaller temperature differences for cooling. Finally, for the gas quench and the condenser no changes were taken into consideration, as these units are subject to technological or external constraints, respectively.

The impact of these modifications is presented in Table 4. It becomes clear that only a few components show a higher avoidable exergy destruction if the operating ranges change. This applies to the gasifier, GT system and the syngas cooler. In contrast, smaller or no potential is identified for the WGS unit, both capture cycles, as well as the gas quench and condenser.

The largest potentials are present for the GT combustion chamber and gasifier, as the changed conditions are more favorable in terms of thermodynamic efficiency. Based on the particular assumptions, the avoidable exergy destruction associated with the gasifier is almost twice that of the GT combustion chamber. Producing superheated HP steam within the syngas cooler is advantageous over the production within the WGS unit due to the larger cooling demand of the syngas cooler. The potential of the GT turbine, being the most complex component for simulation, is calculated to position four. The absolute potential of the GT compressor is almost exhausted. In summary, it becomes clear that the most important components still have some potential for improvement in the future.

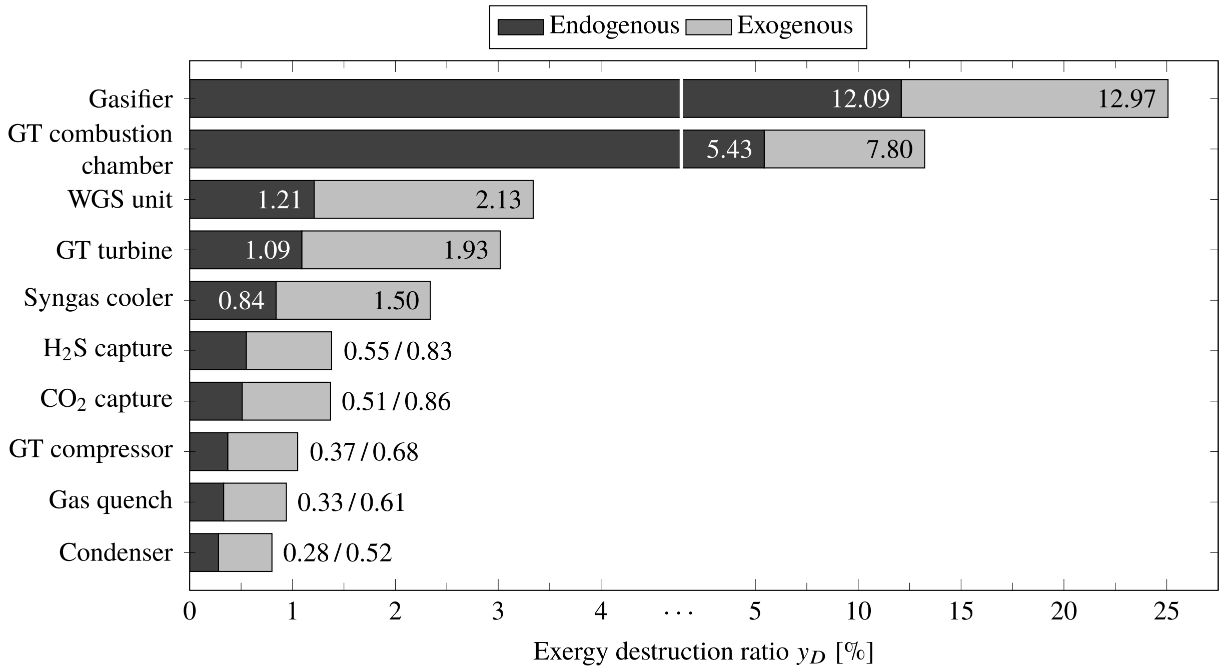

Fig. 3. Splitting the exergy destruction into its endogenous and exogenous parts.

4.2.2 Endogenous and Exogenous Exergy Destruction

The exergy destructions related to the component interactions are shown in Table 4 and plotted in Fig. 3. A large part of the exergy destruction in all components is exogenous even though the proportions differ to some extent. Such a behavior is possibly related to the high level of integration within the system concept. Furthermore, at this level of detail all the exogenous exergy destructions are positive meaning that by improving the performance of other components the exergy destruction within the component being considered decreases.

The gasifier and the GT combustion chamber have the highest values of endogenous exergy destruction due to the irreversible chemical reactions taking place. The share of endogenous exergy destruction for both components is 48.3 and 41.1 %, respectively. All other components analyzed have endogenous exergy destruction shares below 40 %. This is possibly caused by the strong dependence on the operation of the gasifier and GT combustion chamber.

An interesting finding is that the H_2S and CO_2 capture cycles have the third and fourth largest proportion of endogenous exergy destruction. A possible implication is that the separation of pollutants with existing technologies exhibits inherent limitations due to the high energy demand. However, the endogenous amount of the following components is not much different.

As shown above, the gasifier and GT combustion chamber have the highest exergy destruction among all components of the overall system. Therefore, determining the influence that both units have on other subsystems is of special interest. The results of the analyses of binary interactions are collected in Table 5. If component k is part of the subsystem r itself, this component is excluded from the subsystem. Regarding the steam cycle, only the major subunits being the HRSG and the steam turbines were considered.

What is clearly shown is the high interaction between the gasifier and combustion chamber. Particularly, the gasifier strongly influences the combustion chamber (35 % of $\dot{E}_D^{EX}$) since the gas turbine fuel is produced by gasification. In general, the components associated with high exergy destructions in the conventional analysis have a high impact on the particular component. Furthermore, a large share of exergy destruction within the gasifier itself is caused by the other units of the gasification island. In contrast, the interactions of the GT combustion chamber with the remaining components of the GT system are small. Generally, the high mexogenous part of the gasifier and the GT combustion chamber

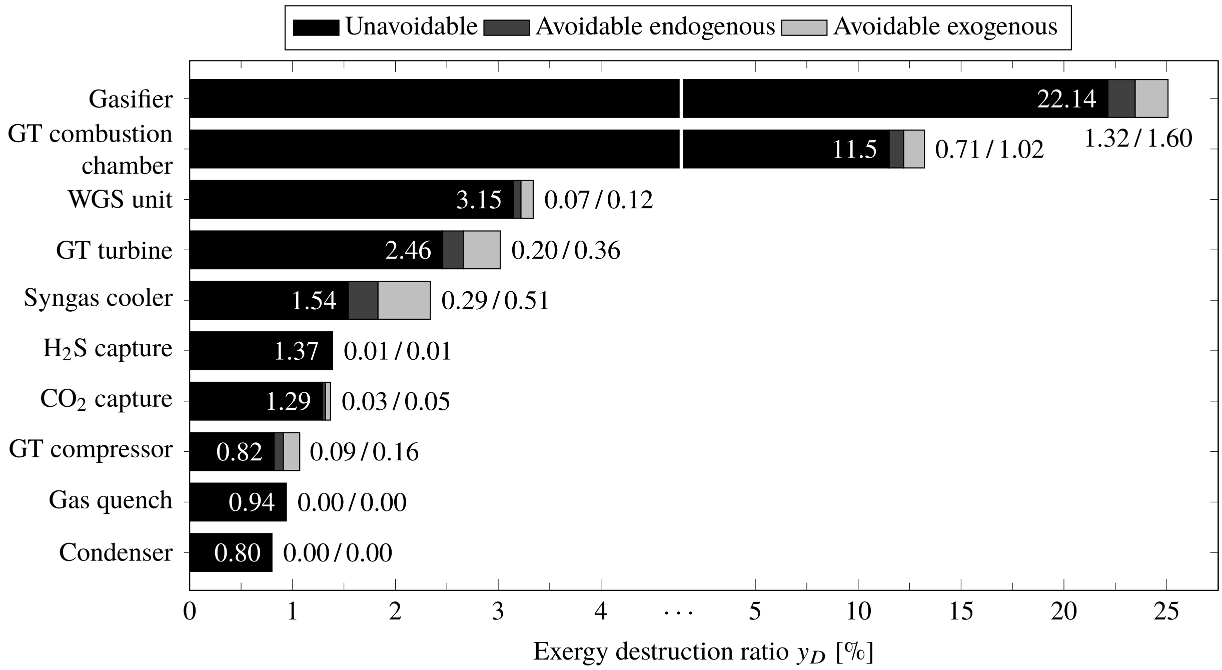

Fig. 4. Results of splitting the exergy destruction into its unavoidable and avoidable endogenous and exogenous parts.

Table 5. Results of the advanced exergy analysis for gasifier and the GT combustion chamber concerning the interactions on subsystem level in [MW].

		Component k	
	Subsystem r	Gasifier	GT comb. chamber
$\dot{E}_{D,k}$		644.9	340.3
$\dot{E}_{D,k}^{EN}$		311.2	139.7
$\dot{E}_{D,k}^{EX}$		333.7	200.6
$\dot{E}_{D,k}^{EX.r}$	ASU	7.0	2.7
	Gasification island	55.5	119.6
	- only gasifier	–	70.0
	AGR	17.3	6.5
	Gas turbine system	122.0	9.0
	- only comb. chamber	82.9	–
	Steam turbine	4.0	1.5
	HRSG	12.9	4.9
	CO_2 compressor	3.8	1.5
$\dot{E}_{D,k}^{mexo}$		111.2	54.9

reveal the high interdependencies within the IGCC concept. For both components the mexogenous part is calculated to about one third of the exogenous exergy destruction. This demonstrates the effect that any irreversibilities within other subsystems or units cause additional exergy destructions to the gasifier and GT combustion chamber. This effect results in a larger syngas flow within the system that is required to compensate the irreversibilities within other subsystems.

4.2.3 Combined Splittings of Exergy Destruction

Based on the combined splittings, the most promising components are identified to determine the priorities in a potential improvement strategy. The avoidable endogenous and exogenous exergy destructions are shown in detail in Table 4 and Fig. 4. The results from the former analyses obviously do not change much within this analysis.

Basically, the gasifier and the GT combustion chamber should be improved first, as both components exhibit the highest potential in independent improvements indicated by the large endogenous avoidable exergy destruction. If modifications in the operating range of both components can be practically realized, positive effects for other components likely occur. To a smaller extent, the GT turbine and the syngas cooler should be considered for standalone improvement attempts too. Taking into account the constraints identified in the previous analyses, improvements are likely to be realized here. In contrast, no significant improvements in the WGS unit can be realized if no technological modifications are considered. The same applies to the H_2S and CO_2 capture cycles. Based on the highly integrated IGCC concept, it has to be concluded that suggested modifications to the concept have to be examined carefully in order to improve the system's overall efficiency.

5 Conclusions

In the present studies, an approach to understand the inefficiencies within an IGCC concept was made. The advanced exergy analysis approach provides the means to identify the interdependencies between system design and integration as well as the implications that arise for other components and the overall system due to the irreversibilities within each system component.

The avoidable exergy destruction amounts only to a small share compared to the high potentials that are identified by the conventional analysis except for the gasifier and the GT combustion chamber. Basically, subsystems such as the WGS unit, AGR and ASU should not have a high priority in an improvement strategy.

It becomes clear that the ten components with the highest exergy destruction are strongly influenced by other components of the system (52 to 65 % of the exergy destruction is exogenous) depending on the highly integrated design. Furthermore, the gasifier and the GT combustion chamber strongly influence each other as 25 and 35 % of the exogenous exergy destruction are related to this binary component interaction.

With respect to the conducted analyses, it is shown that the major components of the IGCC concept, the gasifier and the gas turbine system, determine the efficiency of the overall system. Furthermore, all subsystems of the IGCC concept show a large amount of exergy destruction caused by the inefficiencies in other components. Due to the high interactions within the system, the major components should be first taken into account, to improve the overall design. Nevertheless, the resulting changes for other components have to be considered even though the overall efficiency is likely to increase.

In order to estimate the influence of modifications within major components, the advanced exergy analyses should be conducted in more detail concerning other components. Moreover, technological changes might be further considered when it comes to the design of future systems.

Nomenclature

AGR	Acid gas removal
ASU	Air separation unit
GT	Gas turbine
HHV	Higher heating value
HP	High-pressure
HRSG	Heat-recovery steam generator
HT	High-temperature
IGCC	Integrated gasification combined-cycle
LHV	Lower heating value
IP	Intermediate-pressure

LP	Low-pressure
LT	Low-temperature
PC	Pulverized coal
TIT	Turbine inlet temperature
WGS	Water gas shift

Mathematical symbols

$\dot{E}$	Exergy rate [MW]
y	Exergy destruction fraction [%]

Greek symbols

ϵ	Exergetic efficiency [%]

Subscripts and superscripts

ar	As-received
AV	Avoidable
D	Destruction
EN	Endogenous
EX	Exogenous
F	Fuel
L	Loss
mexo	Mexogenous
P	Product
UN	Unavoidable

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