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Advanced Exergoeconomic Analysis of a Power Plant with CO_2 Capture

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Abstract

Conventional exergy-based analyses reveal options for improving energy conversion systems, but they suffer from some limitations that are addressed by advanced exergy-based analyses. Advanced exergy-based methods are capable of (1) identifying interdependencies among plant components (endogenous/exogenous values), and (2) revealing the potential for improvement (avoidable/unavoidable values). Thus, data obtained from these methods pinpoint strengths and weaknesses of energy conversion systems and are of great importance when complex plants with a large number of interconnected components are considered. This paper presents one of the first applications of an advanced exergoeconomic analysis to a complex power plant. The plant includes a mixed conducting membrane for oxy-fuel combustion and CO_2 capture. The results show that for the most influential components of the plant, the largest part of investment cost and of the costs of exergy destruction is unavoidable. Additionally, in most cases the interactions among the components are of lower importance and, for the majority of the components, the endogenous parts of the costs (related to the internal operation of each component) are significantly larger than the corresponding exogenous parts (related to component interactions). Nevertheless, relatively strong interactions have been found among the components that constitute the mixed conducting membrane reactor of the plant.

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Keywords: Cost optimization; advanced exergoeconomic analysis; oxy-fuel combustion; combined-cycle power plant; CO_2 capture.

1. Introduction

Advanced exergy-based analyses are novel methods that can identify interactions among plant components, and reveal the real potential for improvement of individual components and overall plants [1–7]. Therefore, the application of these methods is very useful for better understanding the operation of energy conversion systems, especially when complex plants with a large number of interacting components are considered. The methodology of an advanced exergoeconomic analysis has been

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presented in refs. [8,9] and it is, here, further tested and expanded through its first-time application to a complex power plant with CO_2 capture. In an advanced exergoeconomic analysis, the investment costs and the costs of exergy destruction, calculated in a conventional exergoeconomic analysis are split into avoidable/unavoidable and endogenous/exogenous parts. With this distinction, an engineer can focus on the avoidable part of the mentioned quantities and foresee the effect of parameter variations on component interactions. This knowledge can be crucial when large facilities are considered, particularly when component interdependencies are significant. Apart from the improvement suggestions that we obtain from such implementations, computational challenges of the methodology are also brought to surface. Such issues are subject to investigation, in order to improve the interpretation of the method and to simplify its practical implementation.

CO_2 capture in power plants is one of the proposed measures to decrease CO_2 emissions from the combustion of fossil fuels. However, most methods for capturing CO_2 in power plants are energy intensive [3]. Oxy-fuel combustion appears to be a promising alternative to conventional post-combustion methods and it can help decrease the energy penalty associated with CO_2 capture.

In this paper, an advanced zero emission plant with 85% CO_2 capture (AZEP 85) incorporating a mixed conducting membrane (MCM) reactor (see Figure 1) is analyzed using an advanced exergoeconomic analysis [10–12] for the first time. The same plant has been studied using conventional exergy-based analyses, advanced exergetic and exergoenvironmental analyses [3,13,14]. Some key results of the previously reported economic and exergoeconomic analyses of the power plant are also presented here, in order to account for some changes in the main assumptions of the analyses. Additionally, the AZEP is also compared to a conventional power plant (reference plant) that does not include CO_2 capture [3]. The efficiency penalty for capturing CO_2 in the AZEP concept is found to be relatively low, while the cost of the necessary equipment is estimated to be substantial. Thus, possible measures for reducing the overall cost of the plant, especially when these can result in improvements in its overall efficiency, are very valuable.

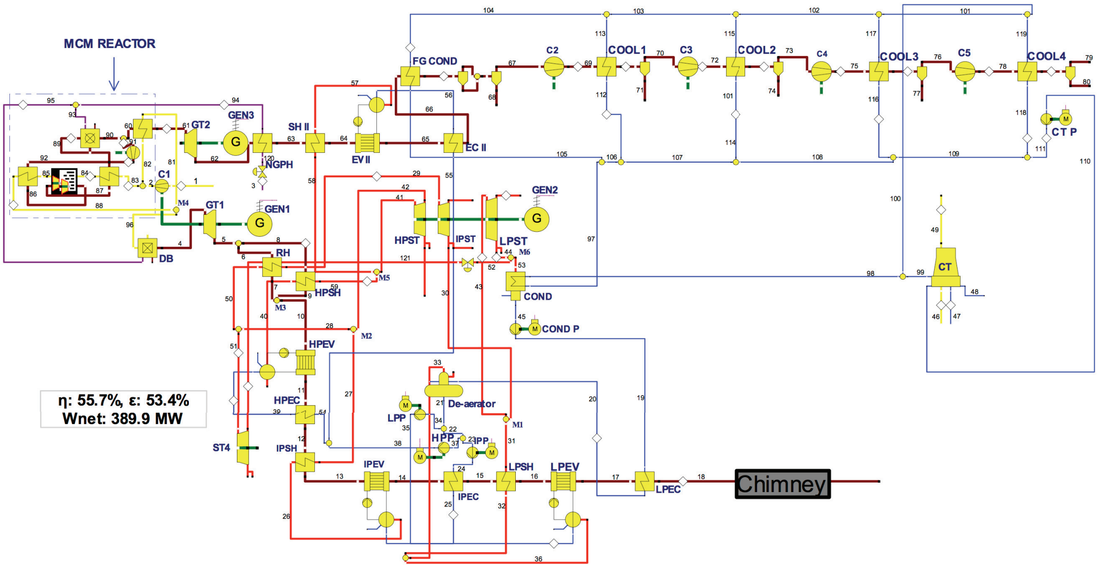

Figure 1: Structure of the AZEP 85

2. Methodology

The main goal of advanced exergoeconomic analysis is to split the investment costs and costs of exergy destruction into endogenous/exogenous and avoidable/unavoidable parts. Avoidable costs show the real potential for improvement. To calculate the unavoidable investment costs, we simulate each component operating under the least favorable conditions (high irreversibilities). The unavoidable cost of some components (e.g., turbomachinery) is predefined, due to limited possible design changes for these components. Although the calculation of avoidable and unavoidable costs is conducted in a rather simple way and depends on the decision maker, it offers us valuable approximate values of avoidable inefficiencies that should be the focus for improvement [3]. The endogenous and exogenous costs are related to internal operational conditions and to component interactions, respectively. The exogenous cost of each plant component is also traced to the specific components that cause it, revealing individual component interactions and additional information about potential for improvement. This tracing includes examination of the plant components in pairs [3]. Lastly, depending on whether the costs can be avoided or not through design modifications, they can be split into avoidable and unavoidable parts, respectively.

The detailed methodological approach of an advanced exergoeconomic analysis is presented in ref. [3].

3. Results

3.1. Results of the advanced exergoeconomic analysis

Splitting the investment cost rates

Table 1: Splitting the investment cost rates (€/h)

	$\dot{Z}_k^{real}$	$\dot{Z}_k^{UN}$	$\dot{Z}_k^{AV}$	$\dot{Z}_k^{EN}$	$\dot{Z}_k^{EX}$	$\dot{Z}_k^{AV}$		$\dot{Z}_k^{UN}$	
						$\dot{Z}_k^{AV,EN}$	$\dot{Z}_k^{AV,EX}$	$\dot{Z}_k^{UN,EN}$	$\dot{Z}_k^{UN,EX}$
C1	1169.3	993.9	175.4	771.7	397.7	115.7	59.7	655.9	338.0
MCM	1192.3	953.9	238.5	407.9	784.4	81.6	156.9	326.3	627.6
GT1	1336.4	1202.8	133.6	970.0	366.4	97.0	36.6	873.0	329.8
CC	745.9	596.7	149.2	584.6	161.3	116.9	32.3	467.7	129.0
DB	276.8	221.5	55.4	179.9	96.9	36.0	19.4	143.9	77.5
MCM LTHX	1113.0	320.2	764.5	847.1	265.8	558.5	206.0	288.7	31.6
MCM HTHX	696.3	108.9	548.8	434.4	261.9	309.8	239.0	124.7	-15.8
HPST	182.6	164.3	18.3	124.4	58.2	12.4	5.8	112.0	52.3
IPST	201.8	181.7	20.2	161.0	40.8	16.1	4.1	144.9	36.7
LPST	489.2	440.3	48.9	376.1	113.2	37.6	11.3	338.5	101.8
ST4	256.7	231.1	25.7	170.0	86.8	17.0	8.7	153.0	78.1
GT2	247.3	222.5	24.7	341.1	-93.9	34.1	-9.4	307.0	-84.5
C5	362.1	307.8	54.3	488.2	-126.1	73.2	-18.9	415.0	-107.2

The assumptions made for calculating the unavoidable investment cost rates, $\dot{Z}_k^{UN}$ can be found in ref. [3]. Most of the costs of the GT system, the steam turbines and the pumps are assumed to be unavoidable, due to very limited modification possibilities in their design. The unavoidable cost of HXs is estimated performing additional, specially designed simulations. In these simulations, each HX is isolated from the other plant components and it is assumed to operate with high irreversibilities, i.e., high temperature differences and pressure drops. The lowest possible cost of production of the component is then estimated. In contrast to the turbomachinery of the AZEP, it is found that most of the investment costs of its heat exchangers (HXs) is avoidable. The results from splitting the investment cost rates for selected components are shown in Table 1.

The endogenous investment cost rate, $\dot{Z}_k^{EN}$, of the components is higher than their exogenous rate, $\dot{Z}_k^{EX}$, with the exception of the MCM and some HXs. In addition, the difference between the absolute values of the endogenous and exogenous investment cost rates is, in some cases, significant. For example, the endogenous investment cost rates are estimated to be four and three times higher than the exogenous rates of the CC and GT1, respectively. For C1, this difference is smaller. As seen in Table 1, the $\dot{Z}_k^{EN}$ of some HXs and the CO_2 compressors (e.g., C5) is higher than their costs in the real process, $\dot{Z}_k^{real}$ (initial simulation). This is related to the increased mass flow rates required in the endogenous case that result in a higher rate of exergy of the product, when compared to the real process. These results show that the investment cost of a component with negative $\dot{Z}_k^{EX}$ increases when other components operate under theoretical conditions (without exergy destruction). Thus, in order to decrease the cost of a component with negative exogenous investment cost, the exergy destruction within the other components must be increased (opposite effects).

The avoidable investment costs indicate that, priority should be given to the components of the MCM reactor: primarily to its two HXs and secondarily to its MCM. The components CC, C1 and GT1 of the main GT system follow in avoidable cost rates. However, with the exception of the MCM LTHX, the cost of the components with the larger investment cost rates is mainly unavoidable. Thus, the investment cost of the plant is largely unavoidable. Additionally, with the exception of the MCM, most of the exogenous values of the plant components are relatively low, when compared to the endogenous values. This shows that component interactions are not as important as the internal operation of the components. Specifically, 73% and 56% of the avoidable investment cost of the MCM LTHX and the MCM HTHX, respectively, can be reduced through operational changes in the components themselves.

Splitting the cost rate of exergy destruction

Table 2: Selected results from splitting the exergy destruction cost rates (€/h)

	$\dot{C}_{D,k}^{real}$	$\dot{C}_{D,k}^{UN}$	$\dot{C}_{D,k}^{AV}$	$\dot{C}_{D,k}^{EN}$	$\dot{C}_{D,k}^{EX}$	$\dot{C}_{D,k}^{AV}$		$\dot{C}_{D,k}^{UN}$	
						$\dot{C}_{D,k}^{AV,EN}$	$\dot{C}_{D,k}^{AV,EX}$	$\dot{C}_{D,k}^{UN,EN}$	$\dot{C}_{D,k}^{UN,EX}$
C1	797.1	438.8	358.3	527.2	269.8	237.7	120.6	289.6	149.2
MCM	275.3	206.8	68.5	166.9	108.4	96.2	-27.7	70.8	136.1
GT1	1176.9	466.3	710.6	702.9	474.0	364.5	346.2	338.4	127.9
CC	5120.2	4668.5	451.8	4017.7	1102.5	358.5	93.3	3659.2	1009.3
DB	1041.6	483.8	557.8	671.8	369.8	357.4	200.4	314.4	169.4
MCM LTHX	467.4	227.5	239.9	224.4	243.0	51.2	188.7	173.2	54.3
MCM HTHX	60.5	41.0	19.5	37.6	22.9	12.0	7.5	25.6	15.4
HPST	186.9	69.2	117.7	103.4	83.4	56.3	61.4	47.2	22.0
ST4	557.2	82.5	474.6	372.1	185.1	317.4	157.2	54.7	27.9
GT2	131.9	31.3	100.6	128.7	3.2	85.5	15.1	43.2	-11.9
NG PH	268.9	2.2	266.8	175.5	93.4	175.0	91.8	0.5	1.7
Air HX	83.0	15.9	67.1	104.2	-21.2	81.7	-14.6	22.4	-6.5

The calculations used for splitting the cost of exergy destruction, $\dot{C}_{D,k}$, are based on equations found in ref. [3]. The results for selected components of the plants are shown in Table 2. As seen, the majority of the HXs, the CC and C1 present high rates of unavoidable exergy destruction. The opposite is true for

GT1, the CO_2 compressors and the high-pressure ST (HPST). The highest avoidable and unavoidable rates of exergy destruction are found for the CC, GT1, the duct burner (DB) and C1. Also, high avoidable cost of exergy destruction is calculated for ST4.

For the CC 91% of the cost rate of exergy destruction is found to be unavoidable. This results in an absolute avoidable cost of exergy destruction of the CC significantly smaller, when compared to other plant components, like GT1 and the DB. Furthermore, 80% of the avoidable cost of the CC is endogenous. Taking into account the avoidable cost of exergy destruction, the plant can be potentially improved through improvement of components GT1, DB, ST4 and, finally, CC.

In summary, similarly to the investment cost rates, the rates of exergy destruction are mostly endogenous for the majority of the components. Thus, most of the costs stem from the operation of the components themselves, and component interactions are, in general, of lower importance. Nevertheless, the component ranking priority for improvement differs significantly between avoidable investment costs and avoidable costs of exergy destruction.

Splitting the exogenous cost rates of investment and exergy destruction

Table 3: Selected results from splitting the exogenous investment cost rate (€/h)[a]

Component, r	$\dot{Z}_k^{EX}$	*Component, r*	$\dot{Z}_k^{EX,r}$	*Component, r*	$\dot{Z}_k^{EX}$	*Component, r*	$\dot{Z}_k^{EX,r}$
CC	161.26	*DB*	0.22	*GT1*	366.45	*CC*	202.46
		MCM LTHX	0.28			*DB*	1.18
		C1	16.70			*MCM LTHX*	0.78
		GT1	24.87			*C1*	27.34
		MCM	0.48			*MCM*	1.47
		ST4	3.94			*ST4*	9.24
		LPST	8.05			*LPST*	14.51
		SUM	105.69 (138.96)			SUM	328.52 (757.44)
		MX	55.57			MX	37.92
DB	96.93	*CC*	37.55	*MCM*	784.44	*CC*	114.35
		MCM LTHX	0.08			*DB*	17.88
		C1	4.29			*MCM LTHX*	13.17
		GT1	6.33			*C1*	-8.89
		MCM	0.13			*GT1*	3.47
		ST4	1.65			*ST4*	3.86
		LPST	3.11			*LPST*	25.36
		SUM	80.76 (403.28)			SUM	452.41 (430.00)
		MX	16.17			MX	332.03
MCM LTHX	265.85	*CC*	28.82	*ST4*	86.76	*CC*	-43.98
		DB	44.11			*DB*	0.47
		C1	31.80			*MCM LTHX*	2.73
		GT1	77.08			*C1*	11.76
		MCM	-99.30			*GT1*	6.04
		ST4	53.97			*MCM*	5.88
		LPST	-82.20			*LPST*	2.05
		SUM	-34.14 (357.00)			SUM	70.49 (405.77)
		MX	299.98			MX	16.28
C1	397.70	*CC*	166.14	*LPST*	113.16	*CC*	31.38
		DB	4.39			*DB*	3.02
		MCM LTHX	1.12			*MCM LTHX*	-7.79
		GT1	27.86			*C1*	11.08
		MCM	1.54			*GT1*	66.52
		ST4	7.54			*MCM*	0.00
		LPST	10.10			*ST4*	-0.25
		SUM	302.97 (611.92)			SUM	75.58 (329.87)
		MX	94.73			MX	37.57

[a] In parentheses the sum of exergy destruction caused by component *k* to the remaining components *r* is shown

Table 4: Selected results from splitting the exogenous cost rates of exergy destruction (€/h) [a]

Component, r	$\dot{C}_{D,k}^{EX}$	*Component, r*	$\dot{C}_{D,k}^{EX,r}$	*Component, r*	$\dot{C}_{D,k}^{EX}$	*Component, r*	$\dot{C}_{D,k}^{EX,r}$
CC	1102.53	*DB*	1.51	*GT1*	474.05	*CC*	145.81
		MCM LTHX	1.90			*DB*	0.43
		C1	114.59			*MCM LTHX*	0.50
		GT1	170.92			*C1*	9.69
		MCM	2.15			*MCM*	1.02
		ST4	27.11			*ST4*	6.70
		LPST	55.32			*LPST*	10.51
		SUM	822.32(-560.5)			SUM	220.70 (605.62)
		MX	280.21			MX	253.35
DB	369.78	*CC*	142.13	*MCM*	108.37	*CC*	32.14
		MCM LTHX	0.22			*DB*	1.67
		C1	15.45			*MCM LTHX*	-1.09
		GT1	23.63			*C1*	3.39
		MCM	0.36			*GT1*	9.11
		ST4	6.15			*ST4*	1.58
		LPST	11.74			*LPST*	3.37
		SUM	272.45 (16.80)			SUM	80.85 (33.25)
		MX	97.33			MX	27.51
MCM LTHX	243.02	*CC*	37.21	*ST4*	185.09	*CC*	-95.71
		DB	2.05			*DB*	1.02
		C1	-13.05			*MCM LTHX*	5.98
		GT1	11.24			*C1*	25.70
		MCM	-9.92			*GT1*	11.88
		ST4	5.35			*MCM*	12.87
		LPST	-4.77			*LPST*	4.48
		SUM	138.75 (10.08)			SUM	151.85 (76.26)
		MX	104.27			MX	33.24
C1	269.82	*CC*	113.52	*LPST*	179.60	*CC*	34.02
		DB	1.79			*DB*	3.27
		MCM LTHX	0.53			*MCM LTHX*	-8.46
		GT1	19.04			*C1*	12.01
		MCM	0.76			*GT1*	72.12
		ST4	5.15			*MCM*	0.00
		LPST	6.90			*ST4*	-0.25
		SUM	205.15 (350.05)			SUM	81.70 (109.45)
		MX	64.67			MX	103.39

[a] In parentheses the sum of exergy destruction caused by component *k* to the remaining components *r* is shown

Although the endogenous costs are higher compared to the exogenous costs, the sources of the exogenous costs reveal individual component interactions and additional information about improvement potential. The results from splitting the exogenous costs for the components with the highest investment-related and exergy-destruction-related costs are shown in Tables 3 and 4, respectively. The values shown in parentheses show the exergy destruction caused by component k to the remaining components of the plant. The values designated as MX show the mexogenous (mixed exogenous) costs. For a plant component, this mexogenous cost is calculated as the difference between its initially calculated exogenous cost (shown in Tables 1 and 2) and the sum of the split parts caused to it by each of the remaining components (Tables 3 and 4, complete tables can be found in [3]). The mexogenous costs stem from secondary interactions during these detailed calculations and cannot be eliminated nor ignored. Further information can be found in refs. [9, 19]. As seen in Table 3, the main source of the exogenous investment cost of the CC is GT1. Furthermore, the main source of the exogenous investment cost rate of C1, GT1 and the DB is the CC. Overall, the effect of the CC on the investment costs of the remaining components is critical, since its operation is responsible for large parts of the costs of other plant components. However, the exogenous investment cost of the CC (shown in parentheses) is relatively low, due to its opposing effect on some components (mainly those processing the CO_2 stream). The highest effect is calculated for GT1, followed by C1, the MCM HTHX (436.7 €/h) and the MCM (because of their large influence on the CO_2 compressors).

Similar results are obtained when splitting the costs of exergy destruction (Table 4) with the difference that here the CC has the second highest effect on the remaining components of the plant (although negative). This result is mainly associated with the opposing effect the component has on the components of the CO_2 compression unit.

When examining the mexogenous values, significantly high mexogenous investment costs are found for the MCM and the MCM LTHX because of simultaneous interactions among these components and other plant components. Furthermore, high mexogenous costs of exergy destruction are found for GT1 and the CC of the plant, mainly due to interactions between these two components.

4. Conclusions

In this paper, the investment costs and the costs of exergy destruction of the components of an oxy-fuel, advanced zero emission plant with CO_2 capture have been split into avoidable/unavoidable and endogenous/exogenous parts for the first time. It was found that the largest part of the costs for the most influential components of the plant is unavoidable. Moreover, for both the investment costs and the costs of exergy destruction, the interactions among the components (represented by the exogenous part of the costs) are not very strong, because the endogenous costs are significantly larger for the majority of the components. Nevertheless, intense component interactions were revealed among the components of the mixed conducting membrane reactor incorporated in the plant.

From splitting the investment costs and the costs of exergy destruction we obtain different suggestions on improvement priorities of the plant components. For example, although the combustion chamber is ranked in a similar position based on both investment and exergy destruction costs, the expander of the main gas turbine system is ranked first when the costs of exergy destruction is split and sixth when the investment costs are split. These differences between the two types of costs depend on the different assumptions met in each case.

Overall, advanced exergy-based analyses can help engineers improve structures for realizing CO_2 capture in power plants. The component priority ranking provides important assistance for further improvement attempts of a power plant and facilitates the optimization of a complex structure.

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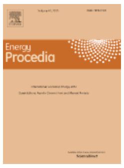

Biography

Dr. Fontina Petrakopoulou is a research associate in the Unit of Environmental Science and Technology at the National Technical University of Athens (NTUA). She is an energy engineer and performs thermodynamic, economic and environmental analyses of energy conversion systems.