Energy 45 (2012) 23–30

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Environmental evaluation of a power plant using conventional and advanced exergy-based methods[☆]

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ARTICLE INFO

Article history:
Received 3 September 2011
Received in revised form
12 December 2011
Accepted 17 January 2012
Available online 7 March 2012

Keywords:
Exergy-based methods
Advanced exergoenvironmental analysis
Life cycle assessment
Combined-cycle power plant

ABSTRACT

An advanced exergoenvironmental analysis combines an advanced exergetic analysis with a life cycle assessment. This allows the environmental impacts of an energy conversion system to be split into avoidable/unavoidable and endogenous/exogenous parts, revealing improvement potential and component interactions. This paper presents the application of an advanced exergoenvironmental analysis to a combined-cycle power plant based on results obtained by a life cycle assessment and a conventional exergoenvironmental analysis. The results are discussed, while possible improvements for reducing the environmental impacts are noted.

Due to its dominant role with respect to exergy destruction, the combustion chamber causes most of the environmental impact within the plant, 68% of which is found to be unavoidable. Evaluating the overall structure, we find that for the majority of the components, most of the environmental impact is unavoidable, a fact that limits the potential for improvement of the plant considerably. We also find that most of the environmental impact of the plant is endogenous, i.e., component interactions are of lower significance. In total, the plant can potentially be improved by enhancing the performance of the combustion chamber, the expander, the compressor and the low-pressure steam turbine.

1. Introduction

The main objective of the implementation of an exergy-based approach is to find appropriate trade-offs between fuel use and investment cost or environmental impact, in order to improve a process. In the 1990s, environmental protection started attracting significant scientific attention and the incorporation of sustainability criteria in engineering sectors started blooming [1]. Scarcity of resources, pollution of the environment caused by energy conversion processes and the incorporation of sustainability considerations into various processes all became widely examined topics. The combination of environmental factors with the concept of exergy was facilitated through work by Szargut [2], Frangopoulos, von Spakovsky [1,3], Rosen, Dincer, [4] Gong, Wall [5,6] and Tsatsaronis and co-workers (e.g., [7,8]). The methodology of the conventional exergoenvironmental analysis used in this paper is presented by Meyer et al. in [8].

Although very useful, *conventional* exergy-based analyses have some significant limitations. They do not provide information about either (1) component interactions or (2) real potential for improvement [9]. To address the shortcomings of the conventional methods, *advanced exergetic, exergoeconomic and exergoenvironmental analyses* have been developed and applied over the last 12 years at the Technical University of Berlin [9–16]. In advanced exergy-based analyses, the thermodynamic inefficiencies, costs and environmental impacts associated with each plant component are split into endogenous/exogenous, avoidable/unavoidable parts, as well as into their combined parts: avoidable endogenous/exogenous and unavoidable endogenous/exogenous parts. Overall, advanced exergy-based analyses provide valuable information on how and to what extent, changes in a plant component affect the operation, costs and environmental impact of the remaining plant components and the plant as a whole. In addition, with these approaches the real potential for improvement is revealed through the distinction between avoidable and unavoidable parts. Such results save engineering time and shed light onto the necessary steps needed for the improvement of a system. Until today, advanced exergy-based methods have only been applied to relatively simple systems [17–19]. This paper presents one of the first complete applications of the advanced exergoenvironmental

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doi:10.1016/j.energy.2012.01.042

method to a complex power plant. The plant is referred to as *reference plant* because it has been used as the base case for the simulation, evaluation, and comparison of power plants with various technologies for CO_2 capture. Results of the exergetic, exergoeconomic and exergoenvironmental analyses of the reference plant can be found in [12,20–22].

2. Methodology

2.1. Life cycle assessment (LCA)

An LCA is used to assess the environmental impact (EI) associated with a product over its lifetime [8] and it is carried out following the guidelines of international standard approaches (ISO 14004). The quantification of environmental impacts caused by depletion and emissions of a natural resource can be carried out using different life cycle impact assessment methods. The damage-oriented impact analysis method Eco-indicator 99 is considered here [23]. Eco-indicator 99 defines three categories of damage: (1) damage to human health, (2) damage to the ecosystem and (3) depletion of resources. After calculating the environmental effects of the different categories, the values are optionally normalized, weighted and the result is expressed in Eco-indicator points (Pts). Depending on the attitude and perspective of different societies, there is a *weighting per perspective* represented by three Archetypes [24]. The archetype of the hierarchists has been adopted in this paper. The standard Eco-indicator 99 inventory values are available for the production and processing of a large number of materials, for transport processes, for disposal scenarios, etc.

In an LCA, the component-related environmental impact of component k, $\dot{Y}_k$, is obtained by considering the entire life cycle of the component. This is represented by the sum of the environmental impact of: (a) construction, $\dot{Y}_k^{\mathrm{CO}}$, (including manufacturing, transport and installation), (b) operation and maintenance, $\dot{Y}_k^{\mathrm{OM}}$ and (c) the disposal, $\dot{Y}_k^{\mathrm{DI}}$, of component k:

$$\dot{Y}_k = \dot{Y}_k^{\mathrm{CO}} + \dot{Y}_k^{\mathrm{OM}} + \dot{Y}_k^{\mathrm{DI}} \qquad (1)$$

The appropriate combination of an LCA with an exergetic analysis assists in understanding the formation of environmental impacts in energy conversion systems at the component level and provides information about the effect of thermodynamic inefficiency on the environmental impacts. An LCA on its own is not capable of allocating the environmental impact of fuel consumption to the specific components of a system. This is performed with the aid of an exergoenvironmental analysis [8].

2.2. Conventional exergoenvironmental analysis

The initial results of the conventional exergoenvironmental analysis of the plant have been presented in [25]. The results presented here differ for two main reasons: (1) The pollutant formation has been defined and calculated as a separate variable; and (2) the EI of CO_2 emissions has been reassessed based on data provided by the Eco-indicator [24]. In an exergoenvironmental analysis, the concepts of exergy and environmental impact are combined. The analysis is performed with a system of equations stated at the component level. The environmental impact balance for component k states that the sum of the environmental impact associated with all i input streams of the component plus the environmental impact of the component itself equals the sum of the environmental impact associated with all j output streams:

$$\sum_{i=1}^{l} \dot{B}_{i,k} - \sum_{j=1}^{m} \dot{B}_{j,k} + \dot{Y}_k + \dot{B}_k^{\mathrm{PF}} = 0 \qquad (2)$$

Here, $\dot{B}_{i/j} = b_{i/j}\dot{E}_{i/j}$ (b: specific EI of stream i/j), $\sum_{i=1}^{l} \dot{B}_{i,k}$ is the sum of the EIs associated with the l steams entering component k, $\sum_{j=1}^{m} \dot{B}_{j,k}$ is the sum of the EIs associated with the m streams leaving component k and $\dot{B}_k^{\mathrm{PF}}$ is the EI of pollutant formation within the component. The latter represents the potential EI that would be caused by the emission of the generated pollutants to the environment. Thus, pollutant formation is defined only when a chemical reaction takes place; in any other case, it is zero. It is calculated as:

$$\dot{B}_k^{\mathrm{PF}} = \sum_{\mathrm{PL}} b_{\mathrm{PL}}^{\mathrm{PF}} \left(\dot{m}_{\mathrm{PL,out}} - \dot{m}_{\mathrm{PL,in}}\right) \qquad (3)$$

where $b_{\mathrm{PL}}^{\mathrm{PF}}$ is the mass specific EI associated with the emission of the PL pollutant to the environment, while $\dot{m}_{\mathrm{PL,in}}$ and $\dot{m}_{\mathrm{PL,out}}$ are the mass flow rates of the pollutant entering and exiting, respectively, component k. The pollutant streams accounted for in a combined-cycle power plant can include: CO, CO_2, CH_4 and NO_x.

In all modern exergy-based methods the fuel/product concept [26,27] is used instead of the input/output concept (Equation (2)) in formulating all balances dealing with exergy, costs and environmental impact. Thus, Equation (2) can be written as:

$$\dot{B}_{F,k} - \dot{B}_{P,k} - \dot{B}_{D,k} + \dot{Y}_k + \dot{B}_k^{\mathrm{PF}} = 0 \qquad (4)$$

The EI of the exergy destruction, $\dot{B}_{D,k}$, is calculated as:

$$\dot{B}_{D,k} = b_{F,k}\dot{E}_{D,k} \qquad (5)$$

where, $b_{F,k}$ is the EI per unit of the exergy of the fuel provided to component k. $\dot{B}_{D,k}$ can then be compared to the component-related EI associated with component k. This is the first step of the evaluation of plant components, in which the components with the highest effect on the overall plant (expressed by the sum $\dot{Y}_k + \dot{B}_{D,k}$) are revealed. Improvement options can be identified through this sum, the exergoenvironmental factor, $f_{b,k}$ (Eq. (6)), and the relative EI difference, $r_{b,k}$ (Eq. (7)):

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{D,k}} \qquad (6)$$

$$r_{b,k} = \frac{(b_{F,k} - b_{P,k})}{b_{F,k}} = \frac{\dot{B}_{D,k} + \dot{Y}_k}{b_{F,k}\dot{E}_{P,k}} \qquad (7)$$

Analogous to the exergoeconomic factor [28], the exergoenvironmental factor expresses the contribution of the component-related EI, $\dot{Y}_k$, to the total EI, $\dot{Y}_k + \dot{B}_{D,k}$, of component k. When the value of $f_{b,k}$ is relatively high, the component-related EI is dominant, whereas when the value of $f_{b,k}$ is low, exergy destruction is dominant. The relative EI difference of component k, $r_{b,k}$, depends on the EI of the component's exergy destruction and its component-related EI and it is an indicator of the potential reduction of its EI. After calculating and evaluating the mentioned variables, design changes are suggested, in order to reduce the EI associated with the product of the overall plant.

2.3. Advanced exergoenvironmental analysis

An advanced exergoenvironmental analysis can be used to examine complex systems in detail and provide analysts with high-certainty information not obtainable by any other approach. In this analysis, the environmental impacts of exergy destruction and pollutant formation are separated into avoidable/unavoidable, endogenous/exogenous and the respective combined parts. In this way, we can estimate the avoidable environmental impact of plant components, as well as the impact associated with component interactions within a complex plant. These estimates can then be used to find trade-offs among avoidable environmental impacts caused by internal inefficiencies (endogenous) or externally by interactions between the component considered and the remaining plant components (exogenous). Because the component-related EI is relatively low, it has not been split here.

In more detail, the avoidable endogenous environmental impact is the part of the environmental impact of a component that can be avoided through operating changes in the component itself. The corresponding exogenous part of the avoidable environmental impact is related with modifications in the remaining components of the plant. It should be noted that the calculation of avoidable and unavoidable values can be somewhat subjective and is conducted in a rather simple way. However, the information obtained is very valuable because it provides us with approximate values of avoidable inefficiencies that should be the focus for improvement. The equations used to perform the analysis are shown in Table A.1, while the equations used for calculating the total avoidable environmental impacts are presented below.

2.4. Calculating the total avoidable environmental impact of pollutant formation and exergy destruction

To identify the real improvement potential of plant components, the total avoidable EI associated with exergy destruction must be calculated at the component level:

$$\dot{B}_k^{\mathrm{PF,AV},\Sigma} = \dot{B}_k^{\mathrm{PF,AV,EN}} + \sum_{\substack{r=1\\ r\neq k}}^{n} \dot{B}_r^{\mathrm{PF,AV,EX},k} \tag{8}$$

$$\dot{B}_{D,k}^{\mathrm{AV},\Sigma} = \dot{B}_{D,k}^{\mathrm{AV,EN}} + \sum_{\substack{r=1\\ r\neq k}}^{n} \dot{B}_{D,r}^{\mathrm{AV,EX},k} \tag{9}$$

Here, $\sum_{\substack{r=1\\ r\neq k}}^{n} \dot{B}_r^{\mathrm{PF,AV,EX},k}$ and $\sum_{\substack{r=1\\ r\neq k}}^{n} \dot{B}_{D,r}^{\mathrm{AV,EX},k}$ are the total avoidable EIs associated with pollutant formation and exergy destruction, respectively, and caused by component k to component r. The avoidable exogenous EI of exergy destruction is calculated as:

$$\dot{B}_{D,r}^{\mathrm{AV,EX},k} = b_{F,r}^{\mathrm{real}} \dot{E}_{D,r}^{\mathrm{AV,EX},k} \tag{10}$$

where, $\dot{E}_{D,r}^{\mathrm{AV,EX},k}$ has been calculated for all components in a preceding advanced exergetic analysis [21].

The term related to the avoidable exogenous EI of pollutant formation is calculated for each component r separately, via the unavoidable exogenous EI of pollutant formation caused by component k, $\dot{B}_r^{\mathrm{PF,UN,EX},k}$:

$$\dot{B}_r^{\mathrm{PF,AV,EX},k} = \dot{B}_r^{\mathrm{PF,EX},k} - \dot{B}_r^{\mathrm{PF,UN,EX},k} \tag{11}$$

The unavoidable exogenous EI of pollutant formation is calculated using the unavoidable endogenous EI, $\dot{B}_r^{\mathrm{PF,UN,EN}}$:

$$\dot{B}_r^{\mathrm{PF,UN,EX},k} = \dot{B}_r^{\mathrm{PF,UN,EN},r+k} - \dot{B}_r^{\mathrm{PF,UN,EN}} \tag{12}$$

$\dot{B}_{D,r}^{\mathrm{PF,UN,EN},r+k} = \dot{E}_{P,r}^{\mathrm{EN},r+k} \left(\frac{\dot{B}^{\mathrm{PF}}}{\dot{E}_P}\right)_r^{\mathrm{UN}}$, with the endogenous exergy of the product $\dot{E}_{P,r}^{\mathrm{EN},r+k}$ being equivalent to the $\dot{E}_{P,r}$, when components r and k operate under real conditions and all remaining components operate under ideal (theoretical) conditions.

The total avoidable EI (Equations (8) and (9)) identifies the components with the largest influence on the overall plant. Actions to reduce their EI should lead to an improvement of the EI of the plant as a whole.

3. Results

The structure of the reference plant can be found in Fig. 1 of Ref. [21]. The plant component names and abbreviations used below are based on this figure. In Table 1, the overall and the relative EI (Pts/kW) of the plant are shown. The EI of pollutant formation $\dot{B}^{\mathrm{PF}}$ of the combustion chamber (CC) has been calculated separately. The specific EI associated with each pollutant and the results of the calculations are also shown in Table 1. Approximately 60% of pollutant formation is related to the CO_2 emissions, while the remaining 40% is related to the plant's NO_X emissions.

To evaluate the overall performance of the plants, the environmental impact of electricity (EIE) has also been calculated (Table 1). The EIE produced by the plant is found to be 25.1 mPts/kWh. This is comparable to the European average EI of low voltage electricity: 26 mPts/kWh [29].

3.1. Conventional exergoenvironmental analysis

Selected results for plant components are shown in Table 2, while more detailed results can be found in Table A.2. In general, in the exergoenvironmental analysis, dissipative components become more important than in the exergoeconomic analysis. Also, the influence of the non-exergy related costs and impacts (investment cost rate and rate of the component-related EI) differs between the exergoeconomic and exergoenvironmental analyses. While the investment cost rates play an important role in determining the total cost [30], the component-related EI is almost negligible. Therefore, the values of $f_{b,k}$ are below 1% for the majority of the components and the overall exergoenvironmental factor of the plant is very low. Thus, environmental performace is primarily determined by the EI of exergy destruction and the specific EI of the fuel. Overall it is found that for the most part, the results of the exergetic and the exergoenvironmental analysis provide the same suggestions for improvement. Differences between the results of the two analyses are noted only for components with significant environmental footprints.

The highest total values of EI correspond to the CC, the expander of the gas turbine (GT1), the low-pressure steam turbine (LPST) and the compressor (C1) of the plant. A reduction in the overall EI could be achieved by increasing the exergetic efficiency of the majority of the components, with the components constituting the gas turbine system first. Nevertheless, a decrease in the exergy destruction within the CC is difficult because it is mostly unavoidable. However, preheating the reactants, as well as using

Table 1
Pollutants, pollutant formation, and environmental impacts.

CO_2 (kg/s, mPts/kg)	38.4, 5.4
NO_X (kg/s, mPts/kg)	0.05, 2749.4
$\dot{B}^{\mathrm{PF}}$ (Pts/h)	1259
$\dot{B}^{\mathrm{PF}}_{CO_2\_\mathrm{capt}}$ (Pts/h)	0
Total EI (10^3 Pts)	2592
Total EI (Pts/kW)	6.3
EIE (mPts/kWh)	25.1

Table 2
Selected results of the exergoenvironmental analysis at the component level.

Component, *k*	$\dot{E}_{F,k}$ (MW)	$\dot{E}_{P,k}$ (MW)	$\dot{E}_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)	$b_{F,k}$ (Pts/GJ)	$b_{P,k}$ (Pts/GJ)	$\dot{B}_{D,k}$ (Pts/h)	$\dot{Y}_k$ (Pts/h)	$\dot{B}_{D,k}+\dot{Y}_k$ (Pts/h)	$f_{b,k}$ (%)	$r_{b,k}$ (%)
C1	242.68	231.30	11.38	95.3	1.56	6.1	6.4	249.71	0.24	249.94	0.09	4.9
CC	729.62	508.76	220.87	69.7	30.23	3.5	5.6	2746.20	0.38	2746.58	0.01	63.3
GT1	551.15	530.67	20.47	96.3	2.80	5.9	6.1	432.58	1.12	433.71	0.26	3.9
LPST	70.99	61.35	9.64	86.4	1.32	7.2	8.8	251.49	0.49	251.98	0.20	21.5
Total	730.58	412.54	300.41	56.5	41.12	3.5	7.0	3735.22	17.33	3752.54	0.46	101.7
Exergy loss	17.63											
$\dot{B}_k^{\mathrm{PF}}$ (Pts/h)	1259											

different GT systems (e.g., a steam-cooled expander) would lead to better efficiencies, and would, thus, decrease the incurred exergy destruction. Overall, in order to reduce the total EI of the plant, more attention should be paid to the exergetic efficiencies of the components.

3.2. Advanced exergoenvironmental analysis

Through an advanced exergoenvironmental analysis, we can define strategies for environmental impact reduction, based on both potential for improvement and component interactions. As mentioned, because exergy destruction is found to be the main source of the environmental impact, the suggestions made by the advanced exergoevironmental analysis generally agree with those obtained by the advanced exergetic analysis [21]. Higher values of the component-related EI are calculated for components constructed with materials with higher EI or for larger components of the plant (e.g., cooling tower, CT).

Selected results of the advanced exergoenvironmental analysis at the component level are presented in Tables 3, 4 and A.3. The results of the advanced exergoeconomic analysis for the same plant can be found in Ref. [20].

3.2.1. Splitting the environmental impact of exergy destruction

The splitting of the EI of exergy destruction, $\dot{B}_{D,k}$, is based on the equations shown in Table A.1. The results for selected components of the plants are shown in Table 3 and A.3. Most of the EI is unavoidable for the majority of the components, with the main exceptions being GT1, the HPST and the IPST. Similar results are obtained for the avoidable endogenous and the unavoidable endogenous EI of the plant. Then, the largest part of the $\dot{B}_{D,k}$ is found to be endogenous, exhibiting lower significance of component interactions. Specifically, the endogenous EI of the CC of the plant is seven times higher than its exogenous EI.

The conclusions drawn by applying the advanced exergoenvironmental analysis are similar to those of the corresponding exergetic analysis [21]. The reference plant can be mainly improved by improving the performance of the components: CC, GT1, LPST and C1 in descending order of importance.

3.2.2. Splitting the environmental impact of pollutant formation

The EI of pollutant formation is defined only for chemical reactions. Depending on whether a component influences the reactor being considered positively or negatively, it can, respectively, decrease or increase the generated emissions. The results from splitting the EI of pollutant formation within the CC of the plant are shown in Table 4. All CO_2 emissions are considered to be unavoidable because complete combustion is assumed. Avoidable emissions include the remaining emissions (NO_X). The endogenous EI has been calculated using data derived from the calculation of the endogenous exergy destruction [21].

The largest part of the EI of pollutant formation is found to be endogenous and unavoidable. Moreover, the avoidable EI of pollutant formation is endogenous and can, therefore, be decreased through changes in the reactor itself. Since the obtained results show relatively low exogenous values, the EI of pollutant formation has not been split further.

3.2.3. Splitting the exogenous environmental impact of exergy destruction

Results from splitting the exogenous EIs for selected components are shown in Table 5. High values of the exogenous EI are found for the components of the GT system of the plant. A large part of the impact of the CC is caused by C1 and GT1: 22% and 34%, respectively. Analogously, large amounts of the impact imposed on C1 and GT1 stem from the CC. It can be seen that the sum of all $\dot{B}_{D,k}^{\mathrm{EX,r}}$ terms is different than the exogenous exergy destruction within the *k*th component. This difference is caused by the simul-

Table 3
Selected results from splitting the environmental impact of exergy destruction (mPts/s).

Component, *k*	$\dot{B}_{D,k}^{\mathrm{real}}$	$\dot{B}_{D,k}^{\mathrm{UN}}$	$\dot{B}_{D,k}^{\mathrm{AV}}$	$\dot{B}_{D,k}^{\mathrm{EN}}$	$\dot{B}_{D,k}^{\mathrm{EX}}$	$\dot{B}_{D,k}^{\mathrm{AV}}$		$\dot{B}_{D,k}^{\mathrm{UN}}$	
						$\dot{B}_{D,k}^{\mathrm{AV,EN}}$	$\dot{B}_{D,k}^{\mathrm{AV,EX}}$	$\dot{B}_{D,k}^{\mathrm{UN,EN}}$	$\dot{B}_{D,k}^{\mathrm{UN,EX}}$
C1	69.4	38.2	31.2	42.3	27.1	19.2	12.0	23.1	15.1
CC	762.8	517.5	245.3	666.8	96.0	215.0	30.3	451.8	65.7
GT1	120.2	45.6	74.6	79.4	40.8	42.8	31.8	36.6	9.0
LPST	69.9	37.0	32.9	44.2	25.7	18.3	14.6	25.9	11.1

Table 4
Splitting the environmental impact of pollutant formation (mPts/s).

	$\dot{B}_k^{\mathrm{PF,real}}$	$\dot{B}_k^{\mathrm{PF,UN}}$	$\dot{B}_k^{\mathrm{PF,AV}}$	$\dot{B}_k^{\mathrm{PF,EN}}$	$\dot{B}_k^{\mathrm{PF,EX}}$	$\dot{B}_k^{\mathrm{PF,AV}}$		$\dot{B}_k^{\mathrm{PF,UN}}$	
						$\dot{B}_k^{\mathrm{PF,AV,EN}}$	$\dot{B}_k^{\mathrm{PF,AV,EX}}$	$\dot{B}_k^{\mathrm{PF,UN,EN}}$	$\dot{B}_k^{\mathrm{PF,UN,EX}}$
CC	349.69	209.5	140.19	332.56	17.12	149.67	−9.48	182.89	26.61

Table 5
Selected results from splitting the exogenous environmental impact of exergy destruction (mPts/s)[a].

Component, *k*	$\dot{B}^{\mathrm{EX}}_{D,k}$	Component, *r*	$\dot{B}^{\mathrm{EX},r}_{D,k}$	Component, *k*	$\dot{B}^{\mathrm{EX}}_{D,k}$	Component, *r*	$\dot{B}^{EX,r}_{D,k}$
CC	96.03	C1	19.32	LPST	25.69	CC	5.09
		GT1	30.54			C1	1.35
		LPST	11.71			GT1	7.73
		SUM	88.64 (48.92)			SUM	14.21 (18.04)
		MX	7.39			MX	11.48
C1	27.07	CC	21.39	GT1	79.35	CC	6.56
		GT1	1.79			C1	1.73
		LPST	0.69			LPST	1.47
		SUM	25.50 (26.62)			SUM	13.03 (63.56)
		MX	1.57			MX	27.78

[a] In parentheses we show the sum of exergy destruction caused by component k to the remaining components r.

Table 6
Avoidable environmental impact of exergy destruction (mPts/s).

Component, *k*	$\sum\limits_{\substack{r=1\\r\neq k}}^{n} B^{\mathrm{AV,EX},k}_{D,r}$	$\dot{B}^{\mathrm{AV,EN}}_{D,k}$	$\dot{B}^{\mathrm{AV},\Sigma}_{D,k}$
CC	17.15 (7.4%)	215.01 (92.6%)	232.16
GT1	15.95 (27.2%)	42.77 (72.8)	58.72
C1	8.82 (31.5%)	19.17 (68.5%)	27.99
LPST	5.35 (22.6%)	18.30 (77.4%)	23.65

taneous interactions among all components and it is called *mexogenous EI*. Relatively high mexogenous values are found for GT1.

3.2.4. Calculating the total avoidable environmental impact of exergy destruction

The total avoidable exogenous EI is calculated using Equations (10) and (11). The results of the most influential components of the plant are shown in Table 6. In the plant, GT1 causes an avoidable exogenous EI similar to that caused by the CC. However, the endogenous impact of the CC is approximately four times higher than that of GT1, resulting in double the overall impact $\left(\dot{B}^{\mathrm{AV},\Sigma}_{D,k}\right)$. Lastly, although C1 has a similar endogenous EI to that of the LPST, its influence on the other components is higher because C1 has a higher total avoidable environmental impact of exergy destruction than the LPST. In summary, in the plant, the CC causes the highest environmental impact, followed by GT1, C1 and the LPST. Overall, improvement strategies for the GT system can involve increasing the temperature of the streams entering the combustion chamber, modification of its cooling system, etc. Alternative improvement steps will be presented in future work.

4. Conclusions

In this paper, a combined-cycle power plant has been analyzed based on a life cycle assessment, conventional and advanced exergoenvironmental analyses. The calculation of the environmental impact of the examined plant is mainly influenced by the environmental impact of the fuel (methane) and the impact associated with the emission of pollutants to the atmosphere. Avoidable/unavoidable and endogenous/exogenous impacts have been calculated at the component level for both the exergy destruction and pollutant formation. In general, the components with higher avoidable impacts are those of the gas turbine system and the low-pressure steam turbine. However, the majority of the environmental impact related to the exergy destruction is found to be unavoidable. Additionally, most of the environmental impact is endogenous, which means that component interactions are relatively low. Thus, the plant should be primarily improved by modifying the internal operation of individual components. We have also shown that the components constituting the gas turbine system can largely influence each other. Thus, improvement strategies should primarily include operating changes of these components, taking into consideration at the same time, the influence of these changes on the remaining components of the system. The results of the plant studied in this paper will be used as reference for comparison and evaluation purposes in future work with the goal of evaluating and improving power plants with CO_2 capture.

Acknowledgments

This research was funded by the European Commission's Marie Curie 6th Framework Programme (CT-2005-019296) as part of the Research Training Network, INSPIRE.

Nomenclature

$\dot{B}$	Rate of environmental impact (Pts/h or mPts/s)
$\dot{E}$	Exergy rate (MW)
f_b	Exergoenvironmental factor (%)
r_b	Relative environmental impact difference (%)
y	Exergy destruction ratio (%)
$\dot{Y}$	Component-related environmental impact (Pts/h)

Super-/Subscripts

AV	Avoidable
UN	Unavoidable
EN	Endogenous
EX	Exogenous
D	Exergy destruction
F	Fuel (exergy)
i,*j*,l,m	Stream
k	Component
L	Loss
P	Product (exergy)
PF	Pollutant formation
PL	Pollutant

Greek symbols

ε	Exergetic efficiency (%)

Abbreviations

C1	Air compressor
CC	Combustion chamber
COND	Condenser
CT	Cooling tower
EC	Economizer
EI	Environmental impact

EIE	Environmental impact of electricity
EV	Evaporator
GT	Gas turbine
GT1	Expander of the gas turbine system
HP, IP, LP	High pressure, intermediate pressure, low pressure
M, Mix	Mixer
P	Pump
RH	Reheater
SH	Superheater
ST	Steam turbine

Appendix

Table A.1. Equations used to perform the advanced exergoenvironmental analysis.

Term	Definition of environmental impact	Environmental impact of pollutant formation, $\dot{B}_k^{\mathrm{PF}}$ and exergy destruction, $\dot{B}_{D,k}$ (for component *k*)	Comments
Endogenous $\left(\dot{B}_k^{\mathrm{PF,EN}}, \dot{B}_{D,k}^{\mathrm{EN}}\right)$	Impact within component *k* associated with the operation of the component itself	$\dot{B}_k^{\mathrm{PF,EN}} = \sum_i b_i^{\mathrm{PF}}(\dot{m}_{i,\mathrm{out}} - \dot{m}_{i,\mathrm{in}})^{\mathrm{EN}}$ $\dot{B}_{D,k}^{\mathrm{EN}} = b_{F,k}^{\mathrm{real}}\dot{E}_{D,k}^{\mathrm{EN}}$	b_i^{PF}: Specific pollutant formation (varies depending on the pollutant) $(\dot{m}_{i,\mathrm{out}} - \dot{m}_{i,\mathrm{in}})^{\mathrm{EN}}$: mass flow difference of pollutant *i*, between outlet and inlet in the endogenous case $b_{F,k}^{\mathrm{real}}$: Specific environmental impact per unit of fuel exergy of component *k* in the real case
Exogenous $\left(\dot{B}_k^{\mathrm{PF,EX}}, \dot{B}_{D,k}^{\mathrm{EX}}\right)$	Impact associated with component *k* caused by the remaining components	$\dot{B}_k^{\mathrm{PF,EX}} = \dot{B}_k^{\mathrm{PF,real}} - \dot{B}_k^{\mathrm{PF,EN}}$ $\dot{B}_{D,k}^{\mathrm{EX}} = \dot{B}_{D,k}^{\mathrm{real}} - \dot{B}_{D,k}^{\mathrm{EN}}$	
Mexogenous $\left(\dot{B}_k^{\mathrm{PF,MX}}, \dot{B}_{D,k}^{\mathrm{MX}}\right)$	Difference between exogenous and sum of split exogenous impacts for component *k*, caused by simultaneous interactions between the component and the remaining components of the plant	$\dot{B}_{D,k}^{\mathrm{MX}} = \dot{B}_{D,k}^{\mathrm{EX}} - \sum_{\substack{r=1 \\ r\neq k}}^{n} \dot{B}_{D,k}^{\mathrm{EX},r}$	$\sum_{\substack{r=1 \\ r\neq k}}^{n} \dot{B}_{D,k}^{\mathrm{EX},r} = \sum_{\substack{r=1 \\ r\neq k}}^{n} (\dot{B}_{D,k}^{\mathrm{EN},r+k} - \dot{B}_{D,k}^{\mathrm{EN}}),$ with $\dot{B}_{D,k}^{\mathrm{EN},r+k} = b_{F,k}^{\mathrm{real}}\dot{B}_{D,k}^{\mathrm{EN},r+k}$
Unavoidable $\left(\dot{B}_k^{\mathrm{PF,UN}}, \dot{B}_{D,k}^{\mathrm{UN}}\right)$	Impact that cannot be avoided	$\dot{B}_k^{\mathrm{PF,UN}} = \sum_i b_i^{\mathrm{PF}}(\dot{m}_{i,\mathrm{out}} - \dot{m}_{i,\mathrm{in}})$ $\dot{B}_{D,k}^{\mathrm{UN}} = b_{F,k}^{\mathrm{real}}\dot{E}_{D,k}^{\mathrm{UN}}$	$\dot{B}_k^{\mathrm{PF,UN}}$: The unavoidable environmental impact of pollutant formation rate includes all emissions of CO_2 when complete combustion takes place (i: CO_2) $\dot{E}_D^{\mathrm{UN}}$: Unavoidable part of exergy destruction rate (calculated in an advanced exergetic analysis with most favorable operating conditions that result in the lowest possible exergy destruction).
Avoidable $\left(\dot{B}_k^{\mathrm{PF,AV}}, \dot{B}_{D,k}^{\mathrm{AV}}\right)$	Impact that can be avoided	$\dot{B}_k^{\mathrm{PF,AV}} = b_{\mathrm{NO}}^{\mathrm{PF}} = \dot{m}_{\mathrm{NO_{X,out}}}$ $\dot{B}_{D,k}^{\mathrm{AV}} = \dot{B}_{D,k}^{\mathrm{real}} - \dot{B}_{D,k}^{\mathrm{UN}}$	$\dot{B}_k^{\mathrm{PF,AV}}$: NO_X emissions that can be avoided assuming, for example, different excess air fraction (λ)
Unavoidable Endogenous $\left(\dot{B}_k^{\mathrm{PF,UN,EN}}, \dot{B}_{D,k}^{\mathrm{UN,EN}}\right)$	Unavoidable impact associated with component *k* caused by the operation of the component itself	$\dot{B}_k^{\mathrm{PF,UN,EN}} = \dot{E}_{P,k}^{\mathrm{EN}}\left(\frac{\dot{B}_k^{\mathrm{PF}^*}}{\dot{E}_{P,k}}\right)^{\mathrm{UN}}$ $\dot{B}_{D,k}^{\mathrm{UN,EN}} = b_{F,k}^{\mathrm{real}}\dot{E}_{D,k}^{\mathrm{UN,EN}}$	$\left(\frac{\dot{B}^{\mathrm{PF}^*}}{\dot{E}_P}\right)_k^{\mathrm{UN}} = \left(\frac{\dot{B}^{\mathrm{PF,UN}}}{E_P^{\mathrm{real}}}\right)_k$
Unavoidable Exogenous $\left(\dot{B}_k^{\mathrm{PF,UN,EX}}, \dot{B}_{D,k}^{\mathrm{UN,EX}}\right)$	Unavoidable impact within component *k* caused by the remaining components	$\dot{B}_k^{\mathrm{PF,UN,EX}} = \dot{B}_k^{\mathrm{PF,UN}} - \dot{B}_k^{\mathrm{PF,UN,EN}}$ $\dot{B}_{D,k}^{\mathrm{UN,EX}} = \dot{B}_{D,k}^{\mathrm{UN}} - \dot{B}_{D,k}^{\mathrm{UN,EN}}$	
Avoidable Endogenous $\left(\dot{B}_k^{\mathrm{PF,AV,EN}}, \dot{B}_{D,k}^{\mathrm{AV,EN}}\right)$	Avoidable impact within component *k* caused by the operation of the component itself	$\dot{B}_k^{\mathrm{PF,AV,EN}} = \dot{B}_k^{\mathrm{PF,EN}} - \dot{B}_k^{\mathrm{PF,UN,EN}}$ $\dot{B}_{D,k}^{\mathrm{AV,EN}} = \dot{B}_{D,k}^{\mathrm{EN}} - \dot{B}_{D,k}^{\mathrm{UN,EN}}$	
Avoidable Exogenous $\left(\dot{B}_k^{\mathrm{PF,AV,EX}}, \dot{B}_{D,k}^{\mathrm{AV,EX}}\right)$	Avoidable impact within component *k* caused by the remaining components	$\dot{B}_k^{\mathrm{PF,AV,EX}} = \dot{B}_k^{\mathrm{PF,AV}} - \dot{B}_k^{\mathrm{PF,AV,EN}}$ $\dot{B}_{D,k}^{\mathrm{AV,EX}} = \dot{B}_{D,k}^{\mathrm{EX}} - \dot{B}_{D,k}^{\mathrm{UN,EX}}$	

Table A.2. Selected results of the exergoenvironmental analysis.

Component, *K*	$\dot{E}_{F,k}$ (MW)	$\dot{E}_{P,k}$ (MW)	$\dot{E}_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)	$b_{F,k}$ (Pts/GJ)	$b_{P,k}$ (Pts/GJ)	$\dot{B}_{D,k}$ (Pts/h)	$\dot{Y}_k$ (Pts/h)	$\dot{B}_{D,k} + \dot{Y}_k$ (Pts/h)	$f_{b,k}$ (%)	$r_{b,k}$ (%)
C1	242.68	231.30	11.38	95.3	1.56	6.1	6.4	249.71	0.24	249.94	0.09	4.9
CC	729.62	508.76	220.87	69.7	30.23	3.5	5.6	2746.20	0.38	2746.58	0.01	63.3
GT1	551.15	530.67	20.47	96.3	2.80	5.9	6.1	432.58	1.12	433.71	0.26	3.9
HPSH	35.07	31.72	3.35	90.5	1.52	5.9	6.8	234.07	1.42	235.49	0.60	15.5
HPEV	43.64	39.91	3.73	91.5		5.9	6.7					13.6
HPEC	28.92	24.91	4.00	86.2		5.9	7.2					23.3

(*continued*)

Component, K	$\dot{E}_{F,k}$ (MW)	$\dot{E}_{P,k}$ (MW)	$\dot{E}_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)	$b_{F,k}$ (Pts/GJ)	$b_{P,k}$ (Pts/GJ)	$\dot{B}_{D,k}$ (Pts/h)	$\dot{Y}_k$ (Pts/h)	$\dot{B}_{D,k}+\dot{Y}_k$ (Pts/h)	$f_{b,k}$ (%)	$r_{b,k}$ (%)
RH	26.47	23.89	2.58	90.3	0.44	5.9	6.8	68.64	0.85	69.49	1.22	15.8
IPSH	0.18	0.12	0.06	69.0		5.9	9.7					65.2
IPEV	6.10	5.67	0.43	92.9		5.9	6.5					11.1
IPEC	1.06	0.87	0.19	82.5		5.9	7.7					30.9
LPSH	1.43	1.04	0.38	73.3	1.06	5.9	9.0	162.97	0.23	163.20	0.14	53.0
LPEV	19.03	15.48	3.55	81.4		5.9	7.8					33.3
LPEC	11.49	7.71	3.78	67.1		5.9	10.1					71.3
LPST	70.99	61.35	9.64	86.4	1.32	7.2	8.8	251.49	0.49	251.98	0.20	21.5
Total	730.58	412.54	300.41	56.5	41.12	3.5	7.0	3735.22	17.33	3752.54	0.46	101.7
Exergy loss	17.63											
$\dot{B}_k^{PF}$ (Pts/h)	1259											

Table A.3. Selected results of the advanced exergoenvironmental analysis (mPts/s).

Component, k	$\dot{B}_{D,k}^{real}$	$\dot{B}_{D,k}^{UN}$	$\dot{B}_{D,k}^{AV}$	$\dot{B}_{D,k}^{EN}$	$\dot{B}_{D,k}^{EX}$	$\dot{B}_{D,k}^{AV}$		$\dot{B}_{D,k}^{UN}$	
						$\dot{B}_{D,k}^{AV,EN}$	$\dot{B}_{D,k}^{AV,EX}$	$\dot{B}_{D,k}^{UN,EN}$	$\dot{B}_{D,k}^{UN,EX}$
C1	69.4	38.2	31.2	42.3	27.1	19.2	12.0	23.1	15.1
CC	762.8	517.5	245.3	666.8	96.0	215.0	30.3	451.8	65.7
GT1	120.2	45.6	74.6	79.4	40.8	42.8	31.8	36.6	9.0
HPSH	15.1	9.9	5.2	11.6	3.5	5.1	0.1	6.5	3.3
HPEVAP	19.7	14.6	5.1	10.5	9.2	2.8	2.2	7.6	7.0
HPECON	21.9	17.9	3.9	11.8	10.1	0.9	3.0	10.8	7.1
RH	23.5	16.0	7.5	13.2	10.3	2.9	4.6	10.3	5.7
IPSH	0.3	0.0	0.3	0.5	−0.2	0.4	−0.1	0.1	0.0
IPEVAP	2.5	1.6	0.9	2.4	0.1	1.0	−0.1	1.4	0.2
IPECON	1.1	0.7	0.4	0.9	0.1	−0.1	0.5	1.0	−0.3
LPSH	2.2	0.9	1.3	1.1	1.1	0.8	0.5	0.4	0.6
LPEVAP	20.8	17.5	3.3	9.8	11.0	0.2	3.2	9.7	7.8
LPECON	22.2	11.5	10.7	14.2	8.0	7.5	3.2	6.7	4.8
HPST	14.9	5.5	9.4	7.8	7.1	4.3	5.1	3.5	2.0
IPST	15.2	6.5	8.7	8.3	6.9	3.7	5.0	4.6	2.0
LPST	69.9	37.0	32.9	44.2	25.7	18.3	14.6	25.9	11.1
COND P	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
HPP	1.1	0.2	0.9	0.4	0.7	0.3	0.6	0.1	0.1
IPP	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
LPP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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