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Post-Combustion CO$_2$ Capture with Monoethanolamine in a Combined-Cycle Power Plant: Exergetic, Economic and Environmental Assessment[1]

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1. Introduction

Post-combustion capture through chemical absorption is the most technologically-mature CO$_2$ capture method, developed about 70 years ago to remove acid gases from natural gas streams (Herzog, 2001). The prominent disadvantage of the method is the significant amount of thermal energy required for the regeneration of the chemicals used, resulting in a considerable efficiency penalty. In recent years, many studies have reviewed different post-combustion technologies and compared the effectiveness of different types of absorbents for chemical absorption (e.g., Kothandaraman et al., 2009; Rubin & Rao, 2002). Analyses have yet to reveal any significant breakthrough, leaving chemical absorption as one of the most energy intensive methodologies for CO$_2$ capture. Nevertheless, the significant advantage of chemical absorption is that existing plants can be retrofitted with a capture unit without further rearrangements. This straightforward application of the technology makes it interesting from both a practical and an economic point of view.

This study evaluates the performance of a combined-cycle power plant with post-combustion CO$_2$ capture using monoethanolamine (MEA plant). The structure and operating conditions of the plant are based on a reference power plant that does not include CO$_2$ capture. The methods used in the evaluation process are exergy-based. In an exergetic analysis the physical and chemical exergies of process streams are calculated and the performance of the plant components is assessed using exergy destruction and exergetic efficiency. The combination of an exergetic analysis with an economic analysis and a life cycle assessment (LCA) constitutes an exergoeconomic and an exergoenvironmental

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[1] The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission

analysis, respectively. In an exergoeconomic analysis, costs are assigned to the exergy of the streams and to the exergy destruction, revealing trade-offs between capital investment and cost of exergy destruction within each component of an energy conversion system. Analogously, in an exergoenvironmental analysis, environmental impacts are assigned to the construction of the components and to the exergy destruction and trade-offs between the environmental impact of component construction and exergy destruction are identified. In all cases, the evaluation takes place both at the component and the plant level.

2. The power plants

2.1 The reference plant

The reference plant is a combined-cycle power plant without CO_2 capture that is used as the base case for the simulation of the MEA plant. A simplified flow diagram of the reference plant is shown in Figure 1, while its detailed diagram can be found in the Appendix (Figure A.1).
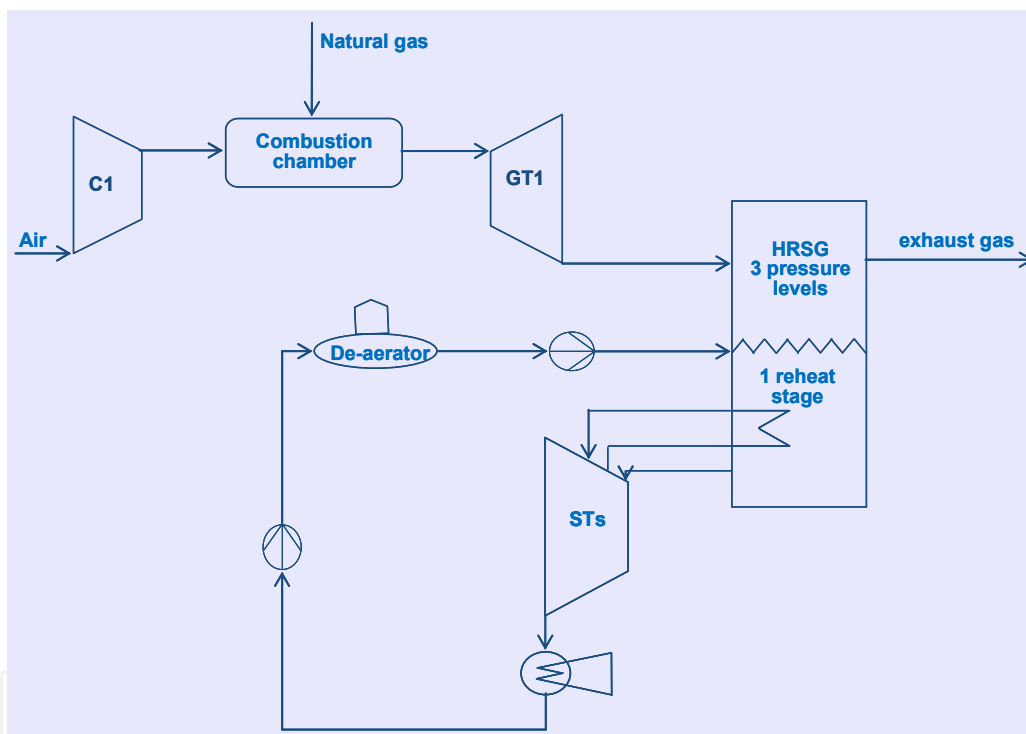

Fig. 1. Simplified diagram of the reference plant.

The plant includes a three-pressure-level heat-recovery steam generator (HRSG) and one reheat stage. A description of the operation and important operating parameters of the plant can be found in Petrakopoulou (2010) and Petrakopoulou et al. (2011a).

2.2 The plant with chemical absorption using monoethanolamine (MEA plant)

The plant with post-combustion capture bears minimal structural changes when compared to the reference plant. The modifications needed to incorporate CO_2 capture here are: (1) the addition of a chemical absorption unit (CAU) at the outlet of the exhaust gases, (2) the extraction of low-pressure steam to produce adequate thermal energy for the regeneration

of the chemical solvent used, and (3) the addition of steam turbines (STs) to drive the flue gas and compressors (C2 & C3-C6 in Figure A.2). The last two points result in a significant decrease in the power output and, consequently, in the efficiency of the overall system. A simple diagram of the plant with chemical absorption capture is shown in Figure 2. The grey box highlights the additional parts of this plant, when this is compared to the reference plant. The detailed flow diagram of the plant is shown in Figure A.2. The flue gas entering the CAU of the plant consists of 3.9% (v/v) CO$_2$, resulting in 38 kg/s of CO$_2$, 85% of which is captured. The solution used consists of 40% MEA (w/w).
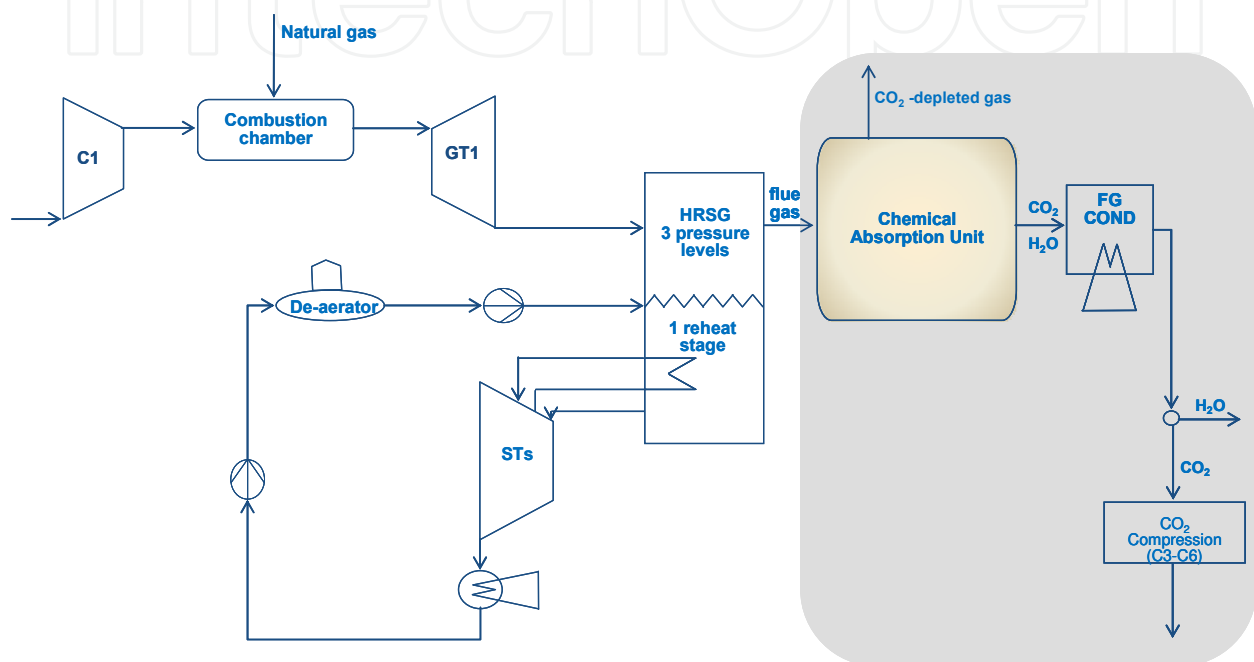

Fig. 2. Simplified diagram of the MEA plant (grey box highlights differences from the reference plant).

In the CAU, the CO$_2$-rich gas enters the absorber flowing upwards, counter-current to the lean MEA solution (Figure 3). After the CO$_2$ is absorbed, the clean gas is exhausted to the atmosphere and the CO$_2$–rich solution is heated in a heat exchanger (HX) and sent to a regenerator. In the regenerator, low-pressure steam extracted from the ST of the plant provides the necessary thermal energy ($\dot{Q}$) to regenerate the absorption medium. In this study, all of the components included in the CAU have been simulated as a black box with the embedded Equations (1)-(4) derived from Rubin & Rao (2002). Two input streams (the steam that provides the regeneration heat and the exhaust gas of the power plant) and three output streams (the exiting liquid water, the CO$_2$ stream and the stream containing the remaining elements of the flue gas) have been considered.

$$\left(L / G\right) = \exp\left(-1.4352 + 0.1239 \times y_{CO_2} + 3.4863 \times \varphi_{lean} + 0.0174 \times \eta_{CO_2} - 0.0397 \times C\right.$$

$$\left. + 0.0027 \times T_{fg,in}\right) \tag{1}$$

$$(Q / L) \ = \ \exp\left(-2.4452 - 0.0037 \times y_{CO_2} - 6.2743 \times \varphi_{lean} + 0.0254 \times C\right) \times 100 \qquad (2)$$

$$\left(T_{fg,out}\right) \ = \ 41.15 + 0.062 \times T_{fg,in} + 1.307 \times y_{CO_2} - 18.872 \times \varphi_{lean} + 0.270 \times C \qquad (3)$$

$$\left(mw_{lean}\right) \ = \ 16.907 + 2.333 \times \varphi_{lean} + 0.204 \times C \qquad (4)$$

Here, C is the MEA concentration in the sorbent (w/w, %), G is the total inlet flue gas flow rate (kmol/h), L is the total sorbent flow rate (kmol/h), mw_{lean} is the average molecular weight of the lean sorbent (kg/kmol), $\dot{Q}$ is the total sorbent regeneration heat requirement (GJ/h), $T_{fg,in}$ is the temperature of the flue gas entering the CO_2 absorber (°C), $T_{fg,out}$ is the temperature of the flue gas leaving the CO_2 absorber (°C), y_{CO_2} is the CO_2 concentration in the inlet flue gas (v/v, %) and φ_{lean} is the lean sorbent CO_2 loading that represents the part of the leftover CO_2 within the regenerated solvent (mol CO_2/mol MEA).

MEA is not included as a chemical compound in the simulation software (EBSILONProfessional), therefore its thermodynamic properties cannot be calculated. This leaves us with two choices: either no consideration of solvent losses (φ_{lean} =0) or consideration of losses that cause a minor violation of mass conservation because no MEA input stream is considered. Without lean solvent CO_2 loading, the MEA is assumed to be fully regenerated. This results in a relatively large amount of regeneration energy (6 MW/kg of CO_2 captured). Therefore, the lean solvent CO_2 loading has been varied from 0.0-0.3 mol CO_2/mol MEA. The influence of this variation on the exergetic efficiency and on the energy requirement of the plant is shown in Figure 4. As can be seen, with a mean value of the lean solvent CO_2 loading (0.2 mol CO_2/mol MEA), the energy requirement is reduced from 6 MW/kg of CO_2, calculated without losses, to 3.7 MW/kg of CO_2. In section 4, the MEA plant is evaluated with both 0.0 and 0.2 mol CO_2/mol MEA (MEA-0 and MEA-0.2), to further assess the effect of this parameter.
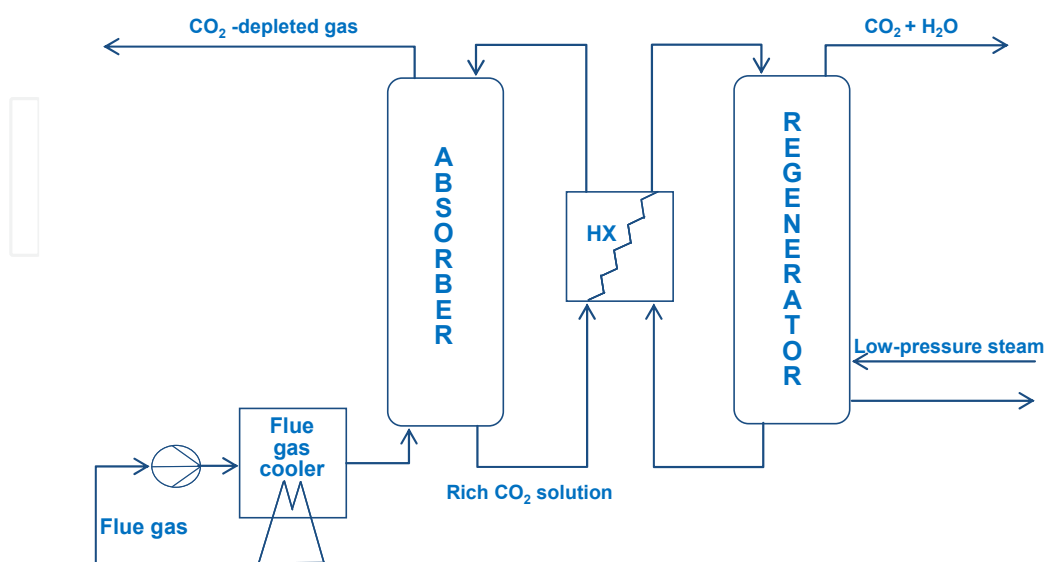

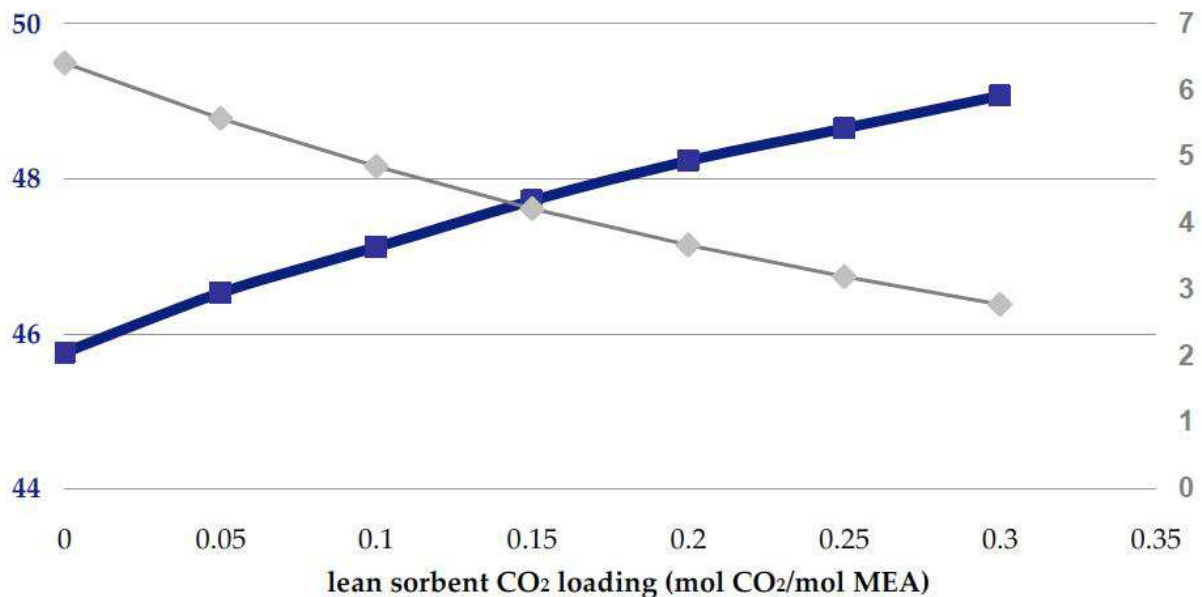
Fig. 3. Simplified diagram of a CAU.

Fig. 4. Exergetic efficiency (%, blue line) and energy requirement (MJ/kg CO$_2$, grey line) relative to the lean sorbent CO$_2$ loading.

3. Methodology

3.1 Exergetic analysis

An exergetic analysis reveals the magnitudes, locations and causes of inefficiencies and losses in an energy conversion system and provides insights that cannot be obtained from an energetic analysis. For a considered process, an exergetic analysis begins with a system of balance equations, formulated at the component level. The rate of exergy of product of component k, , is the exergy of the desired output resulting from the operation of the component, while the rate of exergy of fuel exergy of the same component, $\dot{E}_{F,k}$, is the expense in exergetic resources for the generation of the desired output. The rate of exergy destruction within component k, $\dot{E}_{D,k}$, is calculated as the difference between its rate of exergy of fuel and product ($\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k}$). For the analysis at the component level, streams exiting a component are considered either as part of the product, or they are used in the definition of the component's fuel. Thereafter, exergy loss is only defined for the overall system (tot): $\dot{E}_{L,tot} = \dot{E}_{F,tot} - \dot{E}_{P,tot} - \dot{E}_{D,tot}$.

The exergetic efficiency of component k and that of the overall system consisting of n-components are defined by Equations (5) and (6), respectively:

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \tag{5}$$

$$\varepsilon_{tot} = \frac{\dot{E}_{P,tot}}{\dot{E}_{F,tot}} = 1 - \frac{\sum\limits_{k=1}^{n} \dot{E}_{D,k} + \dot{E}_{L,tot}}{\dot{E}_{F,tot}} \tag{6}$$

General guidelines for the definition of exergetic efficiencies have been proposed in (Lazzaretto & Tsatsaronis, 2006). In dissipative components, such as condensers, intercoolers and throttling valves, exergy is destroyed without any useful product in the component itself; thus, no exergetic purpose can be defined (Bejan et al., 1996; Lazzaretto & Tsatsaronis, 2006). The essential role of these components is to serve other plant components, leading to a more efficient or cost effective operation of the overall system.

Variables related to exergy destruction and exergy loss are the exergy destruction ratio (defined both at the component level and the overall system with, Equations (7) and (8) and the exergy loss ratio (defined only for the overall plant with, Equation 9).

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}} \tag{7}$$

$$y_{D,tot} = \frac{\dot{E}_{D,tot}}{\dot{E}_{F,tot}} \tag{8}$$

$$y_{L,tot} = \frac{\dot{E}_{L,tot}}{\dot{E}_{F,tot}} \tag{9}$$

The exergy destruction ratio is a measure of the contribution of the exergy destruction within each component to the reduction of the overall exergetic efficiency. It can be used to compare dissimilar components of the same system, while the ratios of total exergy destruction and exergy loss can be used to compare different thermodynamic systems.

With an exergetic analysis the main sources of thermodynamic irreversibilities within a plant are identified. If necessary, modifications to the plant can then be applied, in order to reduce these inefficiencies. Since the adoption and/or the development of systems are mainly driven by economics, the thermodynamically optimal design can be used as the starting point for cost reduction and eventually for cost minimization. Nowadays, the concept of *cost* could also be substituted with *environmental impact*, since a rapid increase in energy demand is foreseen that will impact the environment significantly.

3.2 Exergoeconomic analysis

An exergoeconomic analysis is an appropriate combination of an exergetic analysis with economic principles. This is achieved through exergy costing, by which a specific cost c is assigned to each exergy stream of the plant. The specific cost of stream i, c_i, multiplied by the exergy rate of the same stream, $\dot{E}_i$, provides the cost rate $\dot{C}_i$, associated with stream i:

$$\dot{C}_i = c_i \dot{E}_i \tag{10}$$

To perform an exergoeconomic analysis on a plant, cost balances are formulated at the component level resulting in a system of balance equations. For example, the cost balance of component k is stated as follows:

$$\sum_{i=1}^{l} \dot{C}_{i,k} - \sum_{j=1}^{m} \dot{C}_{j,k} + \dot{Z}_k = 0 \tag{11}$$

Here, $\sum_{i=1}^{l} \dot{C}_{i,k}$ is the sum of the cost rates associated with the l steams entering component k,

$\sum_{j=1}^{m} \dot{C}_{j,k}$ is the sum of the cost rates associated with the m streams leaving the component and

Z_k is the rate of investment cost associated with the component.

In the system of balance equations, when the number of unknown stream costs is larger than the number of equations, auxiliary statements are required. For each component, streams entering are assumed to be known, while streams leaving the component are unknown. When the number of the outgoing exergy streams of a component is higher than one (m > 1), m-1 auxiliary equations are needed. The P-principle (on the product side) and the F-principle (on the fuel side) are used to determine the auxiliary equations (Lazzaretto & Tsatsaronis, 2006). The P-principle states that the cost per unit of exergy is supplied to all streams that belong to the definition of the product of the component at the same cost. The F-principle states that the cost, associated with the exergy removed from a component, has the same specific cost as the exergy supplied to the upstream components.

An important outcome of the exergoeconomic analysis is the relation of exergy destruction with costs:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{12}$$

where, $c_{F,k}$ is the average specific cost of fuel of component k.

The calculation of the cost of exergy destruction facilitates the evaluation of plant components and allows comparisons between the cost of exergy destruction and the investment cost for the most important components. The components are first ranked and evaluated based on their total costs $\dot{C}_{D,k} + \dot{Z}_k$. The higher the sum of these costs is, the more significant the effect of the component on the overall plant. The contribution of the capital cost, $\dot{Z}_k$, to the sum of costs is expressed by the exergoeconomic factor f_k, defined by Equation (13).

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{13}$$

Another important variable in the exergoeconomic evaluation is the relative cost difference, r_k. For a given component k, the difference between the specific cost of product, $c_{P,k}$, and the specific cost of fuel, $c_{F,k}$, depends on the cost of exergy destruction, $\dot{C}_{D,k}$, and the related $\dot{Z}_k$.

$$r_k = \left(\frac{c_{P,k} - c_{F,k}}{c_{F,k}}\right) = \frac{\dot{C}_{D,k} + \dot{Z}_k}{c_{F,k}\dot{E}_{P,k}} \tag{14}$$

Information about compromises between the cost of exergy destruction and the investment cost of components, resulting from the exergoeconomic evaluation, can be used in an iterative design improvement of the plant. The objective is to reduce the cost associated with the product of the overall plant.

3.3 Exergoenvironmental analysis

In an exergoenvironmental analysis, the concepts of exergy and environmental impact are combined (Meyer et al., 2009). The component-related environmental impact of component k, $\dot{Y}_k$, is obtained in an LCA considering the entire life cycle of each plant component. It is the sum of the environmental impact of: (a) construction, $\dot{Y}_k^{CO}$, (including manufacturing, transport and installation), (b) operation and maintenance, $\dot{Y}_k^{OM}$ and (c) the disposal, $\dot{Y}_k^{DI}$, of component k:

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \tag{15}$$

Similar to the exergoeconomic analysis, the exergoenvironmental analysis is performed with a system of equations written at the component level. The environmental impact balance for component k states that the sum of the environmental impacts associated with all input streams of the component equals the sum of the environmental impacts associated with all output streams of the same component:

$$\sum_{i=1}^{l} \dot{B}_{i,k} - \sum_{j=1}^{m} \dot{B}_{j,k} + \dot{Y}_k + \dot{B}_k^{PF} = 0 \tag{16}$$

Here, $\dot{B}_{i/j} = b_{i/j}\dot{E}_{i/j}$ (b: specific environmental impact of stream i/j), $\sum_{i=1}^{l} \dot{B}_{i,k}$ is the sum of the environmental impacts associated with the l steams entering component k, $\sum_{j=1}^{m} \dot{B}_{j,k}$ is the sum of the environmental impacts associated with the m streams leaving component k and $\dot{B}_k^{PF}$ is the impact of pollutant formation. The latter is related to the production of pollutants within a component and is charged to the specific component, representing the potential impact that could be caused if the generated pollutants were exhausted. Pollutant formation is defined only when a chemical reaction takes place; in any other case, it is zero. It is calculated as:

$$\dot{B}_k^{PF} = \sum_i b_i^{PF} \left(\dot{m}_{i,out} - \dot{m}_{i,in} \right) \tag{17}$$

where, $\dot{m}_{in}$ and $\dot{m}_{out}$ are the mass flow rates of pollutants entering and exiting component k, respectively. The pollutant streams that are taken into account here include CO_2 and NO_X.

When auxiliary equations need to be formulated, to make the number of the unknowns equal to the number of equations, the same principles are valid as for the exergoeconomic analysis. The environmental impact of the exergy destruction is calculated as:

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$$\dot{B}_{D,k} = b_{F,k}\dot{E}_{D,k} \tag{18}$$

Here, $b_{F,k}$ is the specific environmental impact of the fuel provided to component k. $\dot{B}_{D,k}$ can then be compared to the component-related impact of component k, $\dot{Y}_k$.

The exergoenvironmental analysis not only identifies the components with the highest environmental impact, but also reveals the possibilities for improvement, in order to decrease the environmental impact of the overall plant. These improvement possibilities can be identified through the sum of the component-related environmental impact and the impact of exergy destruction, $\dot{Y}_k + \dot{B}_{D,k}$, the exergoenvironmental factor, $f_{b,k}$, and the relative environmental impact difference, $r_{b,k}$.

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{D,k}} \tag{19}$$

$$r_{b,k} = \frac{\left(b_{F,k} - b_{P,k}\right)}{b_{F,k}} = \frac{\dot{B}_{D,k} + \dot{Y}_k}{b_{F,k}\dot{E}_{P,k}} \tag{20}$$

With the exergoenvironmental factor, the contribution of the component-related impact, $\dot{Y}_k$, to the total environmental impact, $\dot{Y}_k + \dot{B}_{D,k}$ is expressed at the component level. In theory, when the value of $f_{b,k}$ is relatively high, $\dot{Y}_k$ is dominant, whereas when the value of $f_{b,k}$ is low, exergy destruction is dominant. Thus, the higher the exergoenvironmental factor, the higher the influence of the component-related impact on the overall performance of the plant. In practice, when a system works with fossil fuels, the results of the exergoenvironmental factor differ from those of the exergoeconomic factor significantly: the component-related impact is very low when compared to the impact associated with the operation of the plant (exergy destruction).

The environmental impact difference of component k, $r_{b,k}$, depends on the impact of its exergy destruction and its component-related impact. Thus, it is an indicator of the environmental impact reduction potential of the component. After the calculation and evaluation of the mentioned variables, design changes are suggested, in order to reduce the environmental impact associated with the product of the overall process.

4. Results

4.1 Exergetic analysis

In the analysis it was assumed that all power plants are provided with the same amount of fuel. Thus, the derived rate of exergy of product ($\dot{E}_{P,tot}$) depends on the operating characteristics of the plant and the requirements of the CO₂ capture technology. Selected results of the analysis for the overall plants are presented in Table 1 and for the individual components in the Appendix.

As previously discussed, the MEA plant is considered with both zero and 0.2 lean sorbent CO₂ loading (MEA-0 and MEA-0.2). The results of MEA-0.2 agree better with published

work (Rubin & Rao, 2002). Therefore, although MEA-0 will sometimes be used for comparison purposes, MEA-0.2 is considered as the main representative plant for chemical absorption. If not otherwise stated, *MEA plant* refers to MEA-0.2.

	Ref. Plant	MEA-0.2[2]	MEA-0[1]
ε_{tot} (%)	56.5	48.4	45.8
$\dot{E}_{P,tot}$ (MW)	412.5	353.8	334.6
$\dot{E}_{D,tot}$ (MW)	300.4	349.1	368.3
$\dot{E}_{L,tot}$ (MW)	17.6	27.6	27.7
$y_{D,tot}$ (%)	41.1	47.8	50.4

Table 1. Selected results of the exergetic analysis.

The MEA plant results in an efficiency of eight percentage points lower than that of the reference plant. As expected, the main exergy destruction in the plant occurs within its combustion chamber (CC). When the reactants are preheated, the exergy destruction within the reactors decreases (Petrakopoulou, 2010). The exergy destruction within the CC of the MEA plant is the same as that of the reference plant, because the gas turbine (GT) systems of the two plants are identical. The CC is followed by the expander and the compressor of the GT system (GT1 and C1) in descending order of exergy destruction. Apart from the GT system that has a dominant influence due to its high values of $\dot{E}_{D,k}$, other components appear to be equally important. The CAU has the second highest value of exergy destruction among the plant components with 8% of the plant's $\dot{E}_{F,tot}$ being destroyed there. The high-pressure level of the HRSG (HPHRSG) is the most important part of the HRSG in the plant, followed by its respective low-pressure level part (LPHRSG). The low-pressure steam turbine (LPST) also presents relatively significant values of exergy destruction. Lastly, the exergy destruction within the CO_2 compression unit is approximately 2% of the $\dot{E}_{F,tot}$ of the plant.

4.2 Exergoeconomic analysis

The investment cost of the reference plant is calculated to be 213 € million (Petrakopoulou et al., 2011c). For the MEA plants the investment cost is increased by 50%, which is related to the cost of the CAU. Specifically, the investment cost of MEA-0.2 has been found to be 326 € million and that of MEA-0 319 € million. Comparing the two MEA plants, the regeneration requirement in MEA-0.2 is reduced and the CAU is smaller and, therefore, cheaper. However, since a smaller steam mass flow is needed for the CAU, more steam will flow through the condenser of the plant (COND, Figure A.2). Thus, the cooling water requirement of the plant increases, resulting in a larger condenser and a larger cooling tower (CT). Moreover, the first CO_2 compressor (C3) is larger in MEA-0.2 than in MEA-0, because the outlet temperature of the CAU is calculated to be higher. The CO_2 compression unit, i.e., the CO_2 compressors and coolers, is accountable for 13% of the investment cost in the MEA

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[2] 0 and 0.2 stand for the assumed lean sorbent CO_2 loading (0 or 0.2 mol CO_2/mol MEA).

plant. Additionally, the cost of the HRSG of both MEA plants is similar to that of the reference plant. Detailed results of the economic analysis can be found in (Petrakopoulou, 2010).

An important outcome of the exergoeconomic analysis is the correlation of exergy destruction with costs. The cost rate of exergy destruction is calculated at the component level and is compared to the respective investment cost rates. In the reference plant, the three components with the highest cost rates are those constituting the GT system: CC, GT1 and C1. The components that follow the GT system in order of importance are the LPST and the HPHRSG. In the MEA plants, the CAU presents the second highest cost of exergy destruction and total cost, right after the CC of the plant. GT1, C1 and the group of the CO$_2$ compressors follow the CAU. In the MEA plants, the HPHRSG exceeds the STs in cost. Results for selected components of the exergoeconomic analysis are shown in Tables A.1 - A.3 of the Appendix, while the complete results at the component and the stream level can be found in Petrakopoulou (2010).

The relative cost difference, r_k, is found to be high for compressors and pumps, where electric power is used as fuel. This variable shows the theoretical improvement potential of the components. Nevertheless, the exergoeconomic factor, f_k, is the main tool for evaluating the cost effectiveness of a considered component. High values of the exergoeconomic factor for components with high total cost suggest that a reduction of the investment cost should be considered. On the other hand, low values of the factor suggest that a reduction in the exergy destruction should be considered, even if this would increase the investment cost of the component. The low exergoeconomic factors of the CCs of the plants show that most of the components' total cost is related to exergy destruction. This, however, is common for chemical reactors, due to the high level of irreversibilities present there. The exergoeconomic factor of reactors increases when a design with different, more expensive and/or rare materials is considered.

In general, the values of the exergoeconomic factor are within the expected value ranges for the most influential components (Bejan et al., 1996). Exceptions could be the high exergoeconomic factors calculated for the CO$_2$ compressors, suggesting that a decrease in the investment cost of these components (if less expensive components could be employed) should be considered in an attempt to improve the cost effectiveness of the overall plant. A low exergoeconomic factor is calculated for ST4 of the MEA plants. This is due to the exergy destruction within this component, which is found to be high both on its own and when it is compared to the other STs of the plants. Thus, to improve the overall operation of the plants, the efficiency of this ST should be increased. Additionally, for all plants, low factors are calculated in coolers and condensers, where relatively high exergy destruction is found.

Since the plants have the same c_F, the total cost rate of exergy destruction, $\dot{C}_{D,tot}$, depends on the exergy destruction ($\dot{E}_{D,tot}$) within the plants (i.e., $\dot{C}_{D,tot} = c_F \dot{E}_{D,tot}$). The cost of exergy destruction of the MEA plants is larger when compared to that of the reference plant. Specifically, the $\dot{C}_{D,tot}$ of MEA-0 is higher by 23% and that of MEA-0.2 by 16% (see Appendix). As expected, the cost differences are representative of the differences between the $\dot{E}_{D,tot}$ of the MEA plants and that of the reference plant.

Values for the overall plants are shown under *Total* in Tables A.1 - A.3. The overall exergoeconomic factor of the reference plant is calculated to be 40%, while the MEA plants result in overall exergoeconomic factors of 43 and 45%. Additionally, the overall relative cost difference is higher for the plants with CO_2 capture than for the reference plant. This is justified with the additional charges of the supplementary equipment used.

To further compare the costs of the plants, the COE and the cost of avoided CO_2 (COA-CO_2) are considered. The latter shows the added cost of electricity per ton of CO_2 avoided based on net plant capacity (Rubin & Rao, 2002):

$$\text{COA-CO}_2 = \frac{(€ / kWh)_{capture} - (€ / kWh)_{ref.plant}}{\left(t_{CO_2} / kWh\right)^{emitted}_{ref.plant} - \left(t_{CO_2} / kWh\right)^{emitted}_{plant+capture}} \tag{21}$$

The COA-CO_2 relates only to the capture of the CO_2 and it does not include transportation or storage costs.

The resulting levelized COE and the COA-CO_2 for the plants are shown in Table 2. Between the two MEA plants, a lower COE is achieved by MEA-0.2. The COE of this plant is 28% higher than that of the reference plant. When compared to other plants with CO_2 capture (Petrakopoulou et al., 2010b; Petrakopoulou et al., 2011a, 2011b, 2011c), the MEA plants present relatively high costs. These costs are mainly associated with the high energy demand of the solvent regeneration in the CAU and the relatively low percentage of CO_2 capture (85%).

	Ref. Plant	MEA 0.2	MEA 0.0
COE (€/MWh)	74.1	94.6	99.5
COA-CO$_2$ (€/t)	N/A	73.5	92.2

COA-CO_2: Cost of avoided CO_2, COE: Cost of electricity

Table 2. Overall results of the exergoeconomic analysis for the plants.

4.3 Results of the exergoenvironmental analysis

The component-related environmental impacts determined in the LCAs of the plants differ in relative magnitude from costs obtained in the economic analysis. While in the economic analysis, the cost rates (calculated in €/h), are relatively substantial, in the LCA, the component-related environmental impact rates, ($\dot{Y}_k$, in Pts/h) are much lower in scale. Relatively high values are calculated for components constructed with materials of higher environmental impact and for the CTs of the plants, due to their large size. As can be seen in Table 3, the MEA plants have a relatively low increase in relative total environmental impact (Pts/kW), when compared to the reference plant, because of the similar equipment used in both plants. Comparing MEA-0 with MEA-0.2, the differences are also small. While the absorber of MEA-0.2 is smaller and results in a lower impact, its COND and CT are larger. This happens because of the larger mass of steam flowing through the COND, which is a direct result of the lower mass of steam extracted and used in the CAU of this plant (Petrakopoulou, 2010).

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For the LCA, the environmental impact of pollutant formation $\dot{B}^{PF}$ of the reactors of each plant has been calculated separately. The specific environmental impact associated with each pollutant and the results of the calculations, including the impact that is avoided due to CO_2 capture, are shown in Table 4. As can be seen, 60% of pollutant formation in the reference plant is related to the CO_2 emissions of the reference plant, while the remaining 40% is related to its NO_X emissions. The same NO_X emissions are considered for the MEA plants. The environmental impact of pollutants, such as CO_2, can affect the result of the overall analysis. A sensitivity analysis of the impact of CO_2 emissions for the reference and MEA-0.2 plants (with and without consideration of the environmental impact of CO_2 sequestration) is presented in Petrakopoulou (2010). It was found that CO_2 capture becomes meaningful when the environmental impact of CO_2 is higher than 20 Pts/t (when storage is also accounted for). This is a specific environmental impact of CO_2 approximately four times higher than that provided by Goedkoop & Spriensma (2000). Additionally, when CO_2 transport and sequestration are not accounted for, the limit for a positive environmental impact of CO_2 capture decreases the required specific environmental impact of CO_2 to 14 Pts/t.

	Ref. Plant	MEA 0.2	MEA 0.0
Total environmental impact (10^3 Pts)	2,592	3,223	2,871
Total environmental impact (Pts/kW)	6.3	9.1	8.6
EIE (mPts/kWh)	25.1	27.4	29.0

Table 3. Component-related environmental impact and environmental impact of electricity (EIE).

	CO_2		NO_X		$\dot{B}^{PF}$	$\dot{B}^{PF}_{CO_2\_capt}$
	(kg/s)	(mPts/kg)	(kg/s)	(Pts/t)	(Pts/h)	(Pts/h)
Ref. Plant	38.41		0.05		1259	0
MEA 0.2	38.42	**5.4**	0.05	**2749.4**	1270	-646
MEA 0.0	38.42		0.05		1268	-646

Table 4. Environmental impact of overall and avoided pollutant formation due to CO_2 capture.

The component-related impact ($\dot{Y}_{tot}$) differs among the plants. However, this difference is almost negligible and differences among the total impact ($\dot{B}_{D,tot} + \dot{Y}_{tot}$) of the plants are determined by the impact of exergy destruction (see Tables A.1 - A.3). This indicates that the construction is not the key area for reducing the environmental impact of the plants.

In the reference plant, the highest environmental impact ($\dot{B}_{D,k} + \dot{Y}_k$) corresponds to the CC, GT1, the LPST and C1. In the MEA plant, the CC is followed by the CAU, which presents a high environmental impact of exergy destruction. In the exergoenvironmental analysis, dissipative components become more important than in the exergoeconomic analysis: a high

impact is calculated for the condensers (COND and FG COND) of the plants. As already mentioned, in the exergoeconomic and exergoenvironmental analyses, the influence of the non-exergy related costs/impacts (investment cost rate and rate of the component-related impact) is different. Because in the exergoenvironmental analysis the component-related environmental impact is almost negligible, the exergy destruction and the specific environmental impact of fuel are the main deciding factors of the significance of a component. Differences between the results of the exergoenvironmental analysis and that of the exergetic analysis can be noted only for components with high environmental impacts (Petrakopoulou et al., 2010a; Petrakopoulou et al., 2011b).

The total exergoenvironmental factor is similar for the reference and MEA plants because of their similar component-related environmental impact. A reduction in the overall environmental impact could be achieved by increasing the exergetic efficiency of the GT system and of the reactors. In general, a significant decrease in the irreversibilities present in reactors is difficult to be achieved, because these irreversibilities are mostly unavoidable (Petrakopoulou et al., 2011d). However, the preheating of the reactants, as well as the use of different GT systems (e.g., steam-cooled expanders) would lead to better efficiencies, thus decreasing the incurred exergy destruction. In general, in order to reduce the overall impact of the plants, more attention should be given to the effectiveness of the component operation, thus to the exergetic efficiencies of the components.

To compare the overall environmental performance of the plants, the environmental impact of the electricity (EIE) has been calculated (Table 3). The EIE produced by the reference plant is found to be 25.1 Pts/MWh. This is comparable to the European average impact of low voltage electricity: 26 Pts/MWh (Goedkoop & Spriensma, 2000). When compared to the reference plant, the EIE of MEA-0.2 is higher by 2.3 Pts/MWh. Considering that no impact has been considered for pollutants generated by the processing of the solvent used in the plant, the case presented is considered the *best case scenario* of this plant.

5. Conclusion

In this study, a post-combustion CO_2 capture technology (chemical absorption with monoethanolamine) has been evaluated with two different possible energy requirements. A plant incorporating this technology (MEA plant) has been compared with a reference power plant of similar configuration that does not include CO_2 capture. The plants have been analyzed using conventional exergetic, exergoeconomic and exergoenvironmental analyses.

The plant with CO_2 capture presented an (exergetic) efficiency penalty of approximately eight percentage points (48.4%[3]), when compared to the reference plant (56.5%). The relatively high efficiency penalty of the MEA plant is caused by the high energy requirements of chemical absorption that decrease its net power output.

When comparing the cost of the plant with other CO_2 capture technologies (Petrakopoulou, 2010), the MEA plant presents the most economical relative costs based on its power output

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[3] Here, only MEA-0.2 is considered.

(921 €/kW). Additionally, it was found that the cost of exergy destruction of the MEA plant is larger than that of the reference plant. It should be noted that this difference is mainly representative of the differences between the rates of exergy destruction of the plants. Larger differences between the overall costs of the reference and MEA plants are caused by the high investment cost of components used in the CO_2 separation and compression units. The cost of electricity of the MEA plant is found to be 28% higher that of the reference plant. When compared to other capture technologies, and on the basis of the cost of avoided CO_2, large cost differences are observed (Petrakopoulou, 2010). These differences are mainly associated with the high energy demand of the solvent regeneration and the relatively low percentage of CO_2 capture (85%).

In the exergoenvironmental analysis, it was found that the MEA plant presents a low unit increase of the component-related environmental impact (Pts/kW), when compared to the reference plant. However, the component-related environmental impact of the plants is negligible when compared to the impact associated with the exergy destruction that takes place during the operation phase of the plants. The calculation of the overall environmental impact is mainly influenced by the impacts of fuel processing (methane) and the impact of pollutant emission. With data provided by Goepkoop & Spiensma (2000), the environmental impact of the electricity generated in the MEA plant is found to be significantly higher than that of the reference plant (2.3 mPts/kWh higher), due its high efficiency penalty. This raises questions concerning the real environmental and cost viability of chemical absorption with MEA for CO_2 capture in power plants. A sensitivity analysis concerning the variation of the environmental impact of CO_2 emissions showed that post-combustion technology will not decrease the environmental impact of power production, unless a specific environmental impact approximately four times higher than the present estimate is assigned to the CO_2 emissions.

In general, CO_2 capture is a costly process, since it involves either expensive equipment that increases the overall investment cost of the facility or energy-demanding processes that decrease the efficiency, in turn increasing the fuel consumption (i.e., the fuel costs) of a plant. Moreover, the environmental analysis shows that high efficiency reductions result in significant environmental penalties. Thus, with present data, the environmental viability of post-combustion CO_2 capture with chemical absorption using monoethanolamine is questionable, especially when the associated cost expenditure of the technology is also considered.

6. Nomenclature

b	Environmental impact per unit of exergy (Pts/GJ)
$\dot{B}$	Rate of environmental impact (Pts/h)
c	Cost per unit of exergy (€/GJ)
$\dot{C}$	Cost rate associated with an exergy stream, (€/h)
$\dot{E}$	Exergy rate (MW)
f	Exergoeconomic factor (%)

$\dot{m}$	Mass flow (kg/s)
r	Relative cost difference (%)
y	Exergy destruction ratio (%)
$\dot{Y}$	Component-related environmental impact (Pts/h)
$\dot{Z}$	Cost rate associated with capital investment (€/h)

Subscripts

D	Exergy destruction
F	Fuel (exergy)
P	Product (exergy)
i,j	Stream
k	Component
L	Loss

Greek symbols

ε	Exergetic efficiency (%)

Abbreviations

C (1-6)	Compressor
CAU	Chemical absorption unit
CC	Combustion chamber
COA-CO_2	Cost of avoided CO_2
COE	Cost of electricity
COND	Condenser
CT	Cooling tower
EC	Economizer
EIE	Environmental impact of electricity
EV	Evaporator
FG	Flue gas
GT	Gas turbine
HP, IP, LP	High pressure, intermediate pressure, low pressure
HRSG	Heat recovery steam generator
HX	Heat exchanger
LCA	Life cycle assessment
MEA	Monoethanolamine
NG	Natural gas
PF	Pollutant formation
PH	Preheater
RH	Reheater
SH	Superheater
ST	Steam turbine

Fig. A.1. The reference plant.
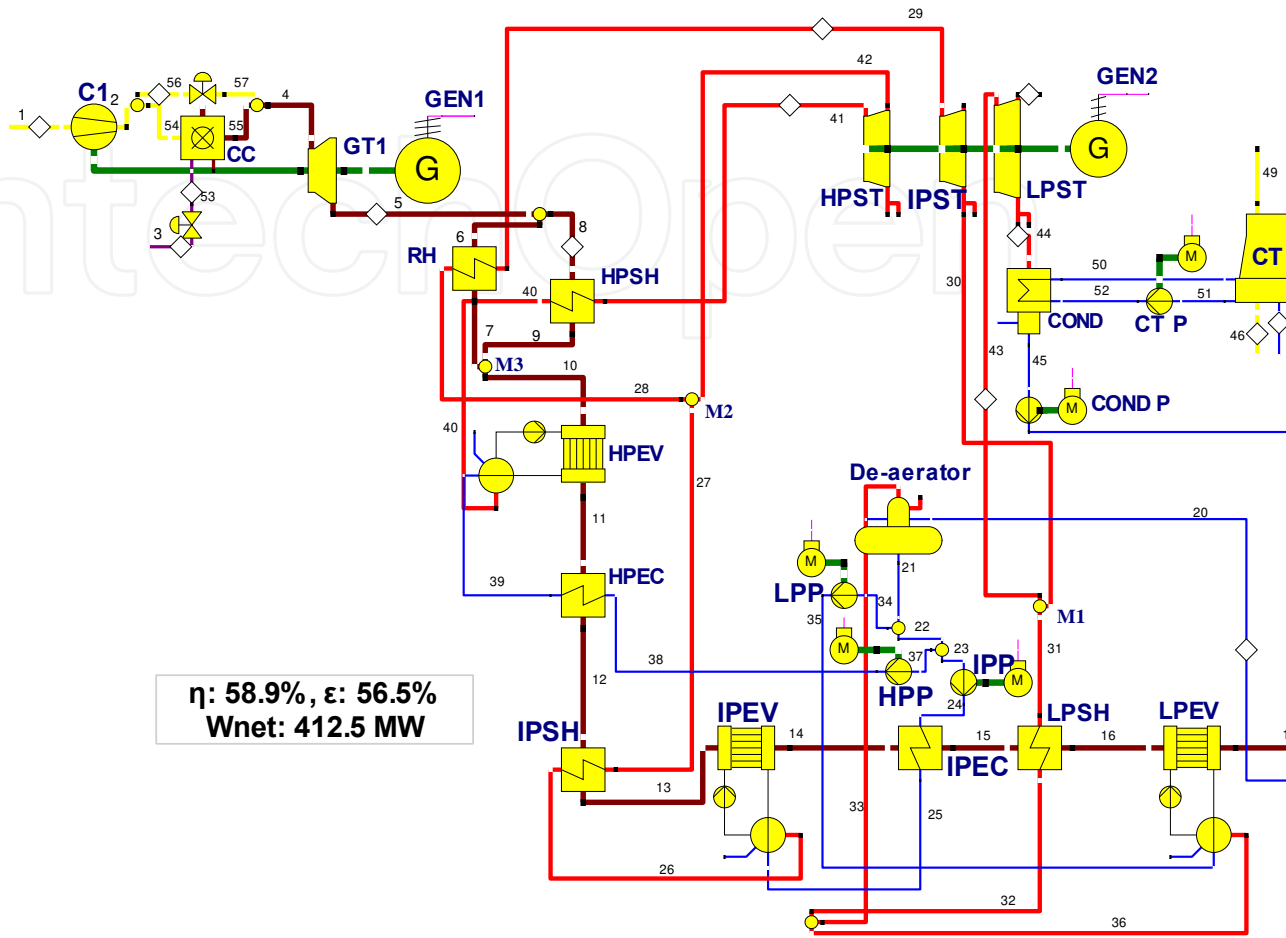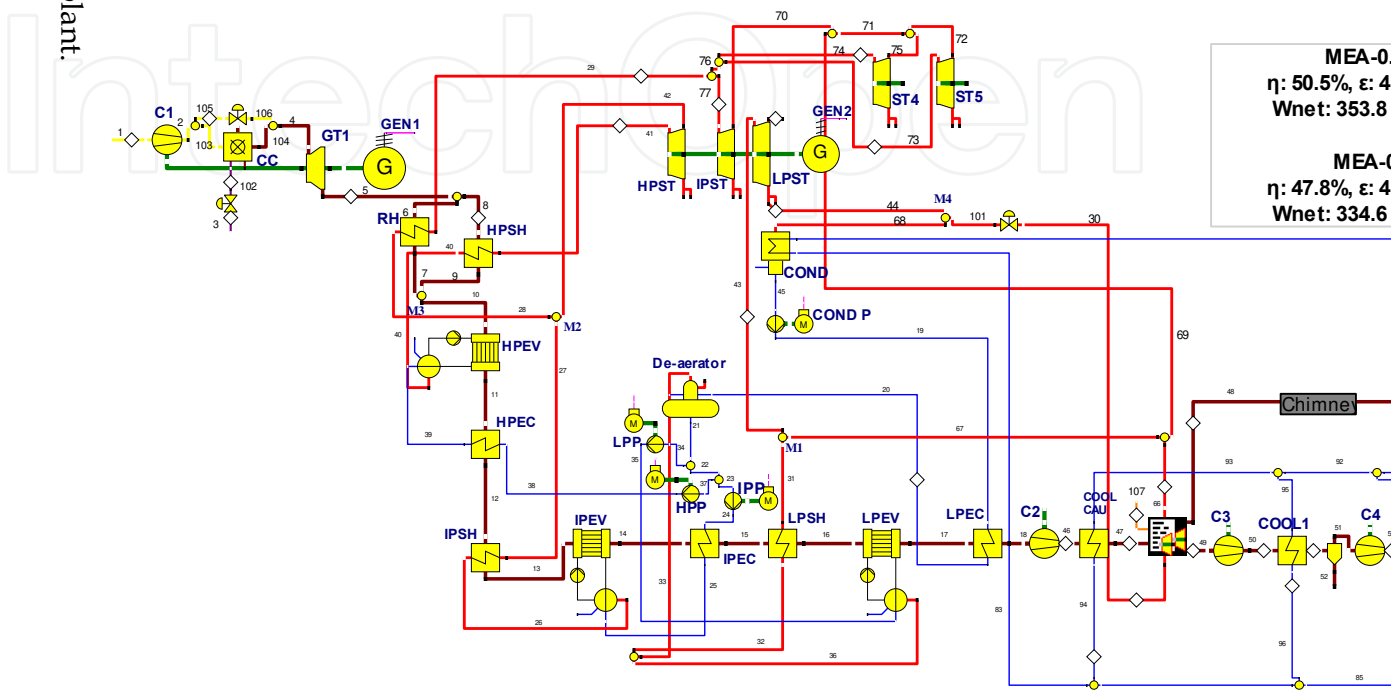
Fig. A.2. The MEA plant.

Component, k	$\dot{E}_{F,k}$ (MW)	$\dot{E}_{P,k}$ (MW)	$\dot{E}_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)	$c_{F,k}$ (€/GJ)	$c_{P,k}$ (€/GJ)	$\dot{C}_{D,k}$ (€/h)	$\dot{Z}_k$ (€/h)	$\dot{C}_{D,k}+\dot{Z}_k$ (€/h)	f_k (%)	r_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)	$f_{b,k}$ (%)	$r_{b,k}$ (%)
CI	242.68	231.30	11.38	95.3	1.56	16.9	19.5	693	1,423	2,116	67.3	15.0	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	9.2	13.7	7,276	1,017	8,293	12.3	49.5	3.5	5.6	2746.20	0.38	2746.58	0.01	63.3
GT	551.15	530.67	20.47	96.3	2.80	15.5	16.9	1,140	1,627	2,766	58.8	9.4	5.9	6.1	432.58	1.12	433.71	0.26	3.9
HPSH	35.07	31.72	3.35	90.5		15.5	19.4					25.6	5.9	6.8					15.5
HPEV	43.64	39.91	3.73	91.5		15.5	19.0					23.1	5.9	6.7					13.6
HPEC	28.92	24.91	4.00	86.2	1.52	15.5	20.4	617	432	1,049	41.2	31.8	5.9	7.2	234.07	1.42	235.49	0.60	23.3
RH	26.47	23.89	2.58	90.3		15.5	19.4					25.4	5.9	6.8					15.8
IPSH	0.18	0.12	0.06	69.0		15.5	35.4					128.8	5.9	9.7					65.2
IPEV	6.10	5.67	0.43	92.9		15.5	20.5					32.8	5.9	6.5					11.1
IPEC	1.06	0.87	0.19	82.5	0.44	15.5	22.3	181	186	367	50.7	44.3	5.9	7.7	68.64	0.85	69.49	1.22	30.9
LPSH	1.43	1.04	0.38	73.3		15.5	29.5					90.9	5.9	9.0					53.0
LPEV	19.03	15.48	3.55	81.4		15.5	24.2					56.4	5.9	7.8					33.3
LPEC	11.49	7.71	3.78	67.1	1.06	15.5	30.8	429	287	716	40.1	99.3	5.9	10.1	162.97	0.23	163.20	0.14	71.3
LPST	70.99	61.35	9.64	86.4	1.32	21.4	29.7	743	764	1,508	50.7	38.5	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	9.2	20.6	9,897	6,519	16,416	39.7	124.8	3.5	7.0	3735.22	17.33	3752.54	0.46	101.7

Exergy loss 17.63

$\dot{B}_t^{PF}$ (Pts/h) 1,259

Table A.1. Selected results at the component level for the reference plant.

| Component k	$\dot{E}_{F,k}$ (MW)	$\dot{E}_{P,k}$ (MW)	$\dot{E}_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)	$c_{F,k}$ (€/GJ)	$c_{P,k}$ (€/GJ)	$\dot{C}_{D,k}$ (€/h)	$\dot{Z}_k$ (€/h)	$\dot{C}_{D,k}+\dot{Z}_k$ (€/h)	f_k (%)	r_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	16.9	19.4	691	1,396	2,086	66.9	14.9	6.1	6.4	249.98	0.24	250.22	0.09	4.9
CC	729.62	508.76	220.87	69.7	30.23	9.2	13.7	7,276	997	8,273	12.0	49.4	3.5	5.6	2746.20	0.38	2746.59	0.01	63.5
GT	551.15	530.67	20.47	96.3	2.80	15.4	16.9	1,137	1,595	2,732	58.4	9.3	5.9	6.1	433.06	1.13	434.18	0.26	3.9
HPSH	35.06	31.72	3.34	90.5		15.4	18.9					22.6	5.9	6.7					13.5
HPEV	43.64	39.91	3.73	91.4		15.4	18.6					20.4	5.9	6.6					11.9
HPEC	28.92	24.91	4.01	86.1	1.52	15.4	19.6	615	424	1,040	40.8	27.3	5.9	7.1	234.36	1.46	235.82	0.62	20.4
RH	26.46	23.89	2.57	90.3		15.4	18.9					22.2	5.9	6.7					13.8
IPSH	0.18	0.12	0.06	69.0		15.4	33.3					115.7	5.9	9.2					57.1
IPEV	6.10	5.67	0.43	92.9		15.4	20.1					30.3	5.9	6.4					9.7
IPEC	1.06	0.87	0.19	82.5	0.44	15.4	21.3	180	182	362	50.3	38.2	5.9	7.5	68.58	0.83	69.41	1.19	27.0
LPSH	1.43	1.05	0.38	73.3		15.4	27.8					80.4	5.9	8.6					46.4
LPEV	19.02	15.47	3.54	81.4		15.4	23.1					49.8	5.9	7.6					29.1
LPEC	11.57	7.81	3.76	67.5	1.05	15.4	28.5	427	284	711	39.9	84.5	5.9	9.5	162.68	0.23	162.90	0.14	61.2
LPST	40.94	35.38	5.56	86.4	0.76	21.4	27.8	428	296	723	40.9	30.0	7.2	8.6	144.91	0.32	145.23	0.22	19.2
C2	18.53	16.93	1.59	91.4		22.5	43.6					94.0	7.2	8.0					10.3
C3	4.33	3.78	0.55	87.3		22.4	132.9					493.8	7.2	25.8					256.9
C4	3.45	2.86	0.59	82.9		22.4	100.1					347.2	7.2	16.3					125.2
C5	3.44	2.82	0.61	82.1	0.46	22.4	77.0	270	2,297	2,567	89.5	244.3	7.2	11.5	87.31	4.90	92.21	5.31	58.3
C6	3.49	2.83	0.66	81.1	0.09	22.4	77.4	53	354	406	87.0	245.7	7.2	11.4	17.13	0.20	17.34	1.18	57.5
CAU	59.28	-	40.59	-	5.56	23.7	-	3,463	1,023	4,486	22.8	-	6.9	-	1006.53	1.75	1008.28	0.17	-
Total	730.58	353.82	349.14	48.4	47.79	9.2	26.3	11,502	9,440	20,942	45.1	187.0	3.5	7.6	4341.17	21.63	4362.80	0.50	120.7

Exergy loss   27.62

$\dot{B}_i^{pr}$ (Pts/h)   1,270

Table A.2. Selected results at the component level for MEA-0.2.

Component, k	$\dot{E}_{F,k}$ (MW)	$\dot{E}_{P,k}$ (MW)	$\dot{E}_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)	$c_{F,k}$ (€/GJ)	$c_{P,k}$ (€/GJ)	$\dot{C}_{D,k}$ (€/h)	$\dot{Z}_k$ (€/h)	$\dot{C}_{D,k}+\dot{Z}_k$ (€/h)	f_k (%)	r_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	19.4	690	1,395	2,086	66.9	14.9	19.4	6.1	6.4	249.94	0.24	250.17	0.09	4.9
CC	729.62	508.76	220.87	69.7	30.23	13.7	7,276	997	8,273	12.0	49.4	13.7	3.5	5.6	2746.20	0.38	2746.59	0.01	63.5
GT	551.15	530.67	20.47	96.3	2.80	16.9	1,137	1,595	2,732	58.4	9.3	16.9	5.9	6.1	432.98	1.13	434.11	0.26	3.9
HPSH	35.06	31.72	3.34	90.5		18.7	615				20.9	18.7	5.9	6.6					12.1
HPEV	43.64	39.91	3.73	91.4		18.4	18.7				19.0	18.4	5.9	6.5					10.6
HPEC	28.92	24.91	4.01	86.1	1.52	19.3	19.6	423	1,039	40.8	24.9	19.3	5.9	6.9	234.32	1.45	235.77	0.62	18.2
RH	26.46	23.89	2.57	90.3		18.6	180				20.6	18.6	5.9	6.6					12.3
IPSH	0.18	0.12	0.06	69.0		32.2	33.3				108.7	32.2	5.9	8.9					51.0
IPEV	6.10	5.67	0.43	92.9		19.9	20.4				29.2	19.9	5.9	6.4					8.7
IPEC	1.06	0.87	0.19	82.5	0.44	20.8	21.2	182	362	50.3	35.0	20.8	5.9	7.3	68.57	0.83	69.40	1.19	24.1
LPSH	1.43	1.05	0.38	73.3		27.0	427				74.7	27.0	5.9	8.3					41.4
LPEV	19.02	15.47	3.54	81.4		22.6	23.1				46.3	22.6	5.9	7.4					26.0
LPEC	11.57	7.81	3.76	67.5	1.05	27.3	28.0	284	711	39.9	77.3	27.3	5.9	9.1	162.65	0.23	162.87	0.14	54.6
LPST	17.84	15.42	2.42	86.4	0.33	29.3	200	134	334	40.1	27.9	29.3	7.5	8.8	65.52	0.19	65.71	0.29	17.4
C2	18.53	16.93	1.59	91.4		43.2	191				95.4	43.2	7.1	7.8					10.3
C3	3.54	3.00	0.54	84.6		153.7	161.9				594.8	153.7	7.1	30.2					325.7
C4	3.45	2.86	0.59	82.9		78.6	83.6				255.3	78.6	7.1	11.8					66.4
C5	3.44	2.82	0.61	82.1	0.33	77.2	82.2	1,435	1,626	88.2	249.1	77.2	7.1	11.3	61.40	1.32	62.72	2.11	58.7
C6	3.49	2.83	0.66	81.1	0.09	77.6	52	360	412	87.3	250.8	77.6	7.1	11.2	16.79	0.20	16.99	1.20	57.8
CAU	86.54	-	67.95	-	9.30	-	5,417	1,086	6,503	16.7	-	-	6.8	-	1658.02	3.50	1661.52	0.21	-
Total	730.58	334.63	368.27	45.8	50.41	9.2	27.6	12,133	9,257	21,390	43.3	201.9	67.8	73.0	4579.01	19.27	4598.28	0.42	7.6

Exergy loss 27.68

$\dot{B}_k^{PF}$ (Pts/h) 1,268

Table A.3. Selected results at the component level for MEA-0.

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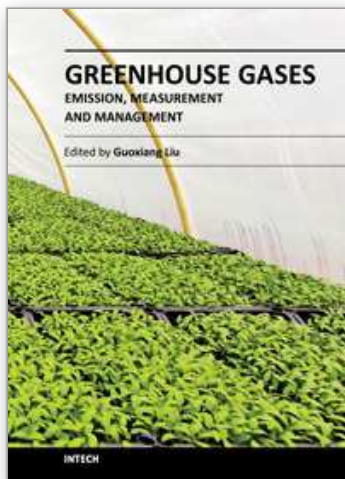
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