Intro to Exergo-Economics

Exergo-Economic Analysis (EEA) is a combination of exergy and economic analysis.

The goal is not only to determine the cost of one or more products (this could be done by a traditional input/output cost analysis) but rather to understand the **process of cost build-up** along the **transformation of energy** and its depreciation, described by the progressive decrease of exergy.

This type of information is very valuable, as it allows to identify the most relevant stages within the process, thereby paving the way to system **improvement and optimization**.

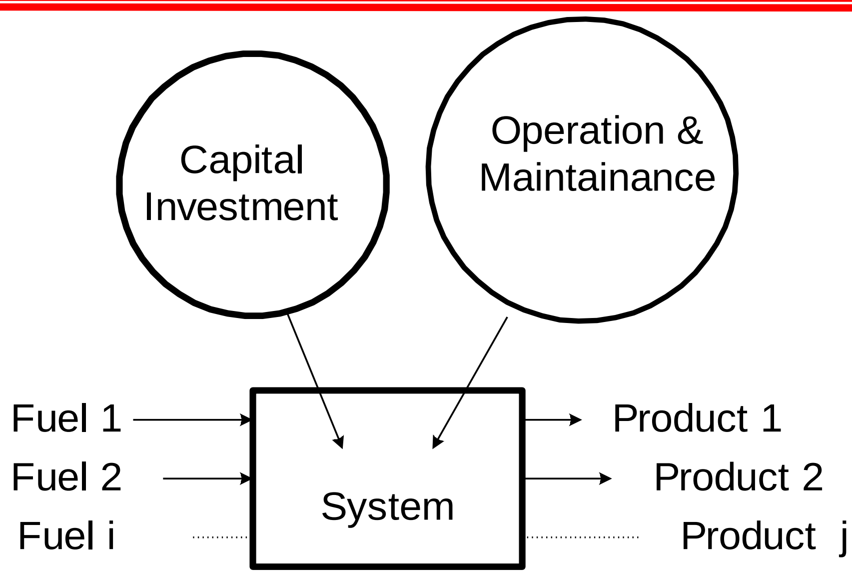
Multiple Products - Maintenance

An Exergo-Economic analysis allows to reconstruct the progressive buildup of the cost of products along the several components within the system, and also to analyze systems with **multiple products**[1] (e.g., heat, electricity, cold and secondary material streams) attributing the correct cost to the products exiting the system in different locations.

An exergo-economic analysis is also very useful for **maintenance**[2], as – once it is done for the reference system – it allows to identify malfunctions and attribute the relative cost, thereby allowing an effective planning of interventions and parts substitution.

[1]El-Sayed Y. M., and Evans R. B. (1970). Thermoeconomics and the design of heat systems. Journal of Engineering for Power 92(1), 27-35.
[2] Reini, M., Taccani, R., On the Thermoeconomic Approach to the Diagnosis of Energy System Malfunctions, Int.J. Thermodynamics, 7, 2, 1-72, 2004

EEA - System level



Referring to the system as a whole, operating in steady-state conditions:

$$\dot{C}_{P,tot} = \dot{C}_{f,tot} + \dot{Z}_{CI,tot} + \dot{Z}_{OM,tot} \qquad \text{EE.1}$$

$\dot{C}_{P,tot}$ is the rate of cost of useful products exiting the system [€/s]

$\dot{C}_{F,tot}$ is the cost rate of fuels entering the system [€/s] (true fuels, but also power or chemical reactants)

$\dot{Z}_{CI,tot}$ is the overall plant capital investement cost rate [€/s] (from design to financing, construction and decommissioning), reduced to unit time considering the life span of the plant

$\dot{Z}_{OM,tot}$ is the overall cost of Operation&Maintenance (personnel, spare parts, consumables, …), also reduced to unit time [€/s]

Capital/Investment + Operation&Maintenance Cost

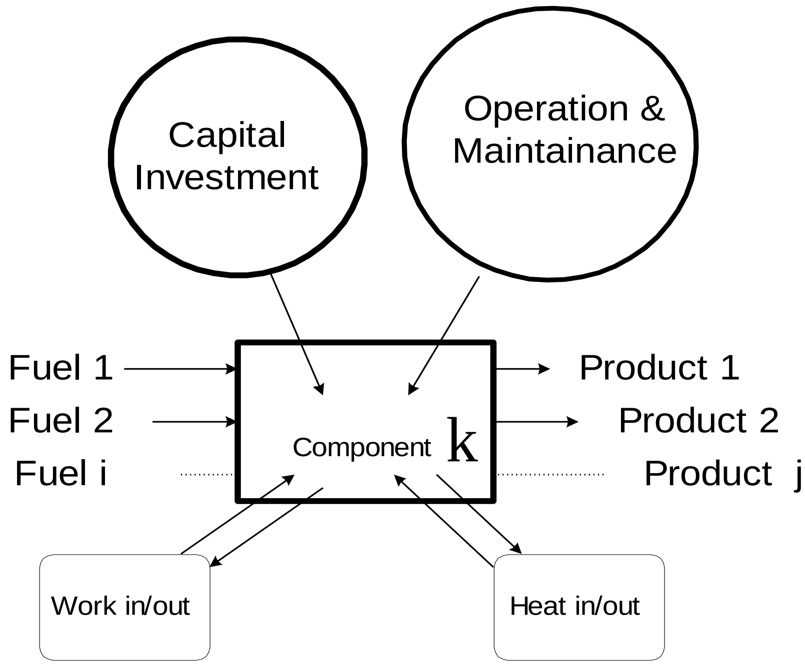
Typically the **Capital & Investment** cost is calculated from a component inventory, adding construction costs and considering discount rates for project financing

The **Operation& Maintenance** cost is generally evaluated on an annual basis, or – when personnel costs are prevailing – over the month. O&M includes spare parts substitution, often performed on a monthly, yearly, 5-yrs or 15 yrs schedule depending on component practice and field of application

Capital Investment and O&M costs in the following will be considered together, reduced to unit time [€/s]:

$$\dot{Z}_{tot} = \dot{Z}_{CI,tot} + \dot{Z}_{OM,tot} \qquad \text{EE.2}$$

EEA - Component level



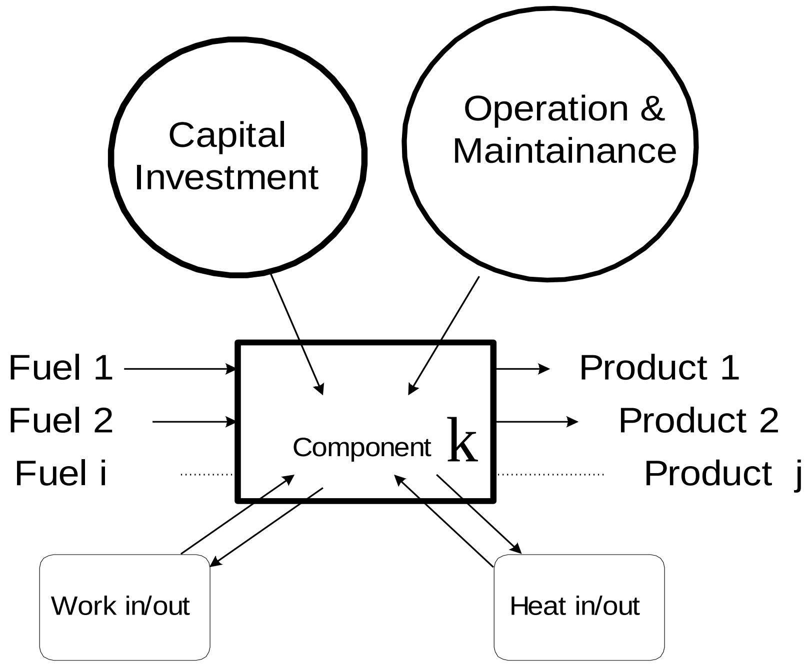
The same approach can be repeated inside the system at the level of component k. It is convenient to separate mass, work and heat interactions. Arrows can represent inputs/outputs across the system boundaries, or exchanges (of matter, work or heat) with other components inside the system.

Separating inputs (i) and outputs (e) one can write the cost balance as:

$$\sum_e (\dot{C}_e + \dot{C}_{Qe} + \dot{C}_{We}) = \sum_i (\dot{C}_i + \dot{C}_{Qi} + \dot{C}_{Wi}) + \dot{Z}_{CI,k} + \dot{Z}_{OM,k}$$

EE.3

EEA - Component level

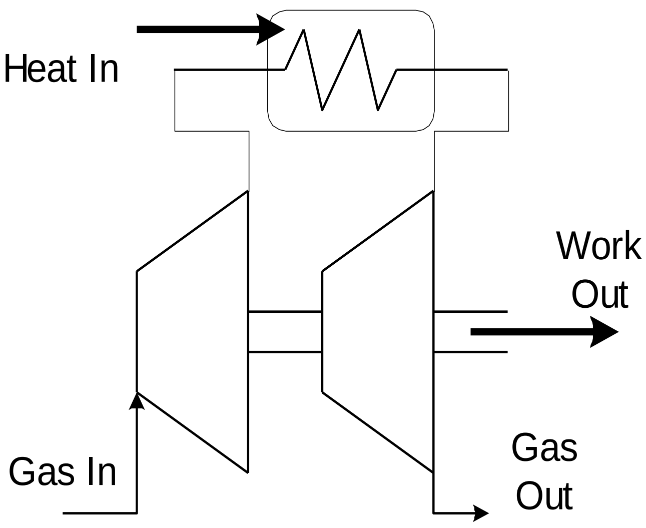


As we are interested in exergy tracking of the costs, it is recommendable to reduce costs to unit exergy c [€/kJ] and use exergy rates E [kJ/s = kW]:

$$\sum_e \left(c_e \dot{E}_e + c_{Qe}\theta_e \dot{Q}_e + c_{We}\dot{W}_e\right) = \sum_i \left(c_i \dot{E}_i + c_{Qi}\theta_i \dot{Q}_i + c_{Wi}\dot{W}_i\right) + \dot{Z}_{CI,k} + \dot{Z}_{OM,k}$$

EE.5

EEA Example 1 – GT with reheat - Balance



$$\underbrace{\dot{C}_{gas,e} + \dot{C}_{W,e}}_{\text{Arrows out}} = \underbrace{\dot{C}_{gas,i} + \dot{C}_{Q,i}}_{\text{Arrows in}} + \dot{Z}_{CI,T} + \dot{Z}_{OM,T}$$

The same equation can be re-formulated using the cost of re-heat c_Q; the cost of work c_W (to be determined), and the cost of the i, e unit exergy:

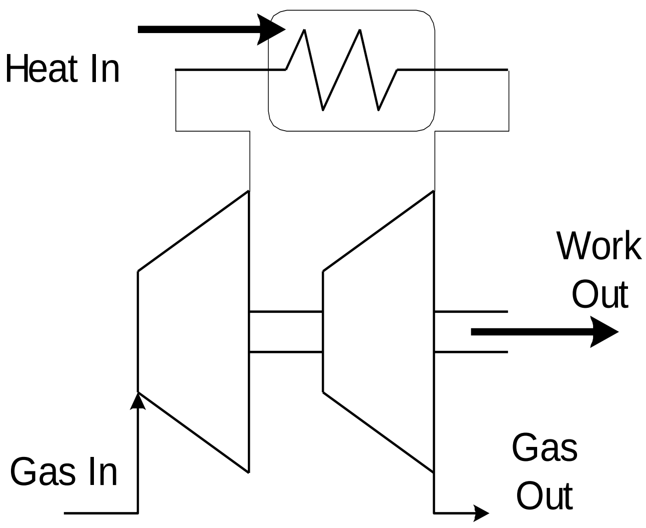
$$c_e \dot{E}_{gas,e} + c_W \dot{W}_e = c_i \dot{E}_{gas,i} + c_Q \dot{Q}_i + \dot{Z}_{CI,T} + \dot{Z}_{OM,T}$$

Or, with the exergy/thermodynamics sign assumption (i=positive; e=negative):

$$c_i \dot{E}_{gas,i} + c_Q \dot{Q}_i - c_e \dot{E}_{gas,e} - c_W \dot{W}_e + \dot{Z}_{CI,T} + \dot{Z}_{OM,T} = 0$$

which is very attractive from a machine-learning point of view.

EEA Example 1 – GT with reheat- Purpose



In Exergo-Economics it is very important to identify the purpose of plant components.

As the purpose of a turbine is producing work, in order to determine c_W [€/MJ or €/kWh], the logical assumption is to consider constant the unit cost of input and output exergy, $c_i = c_e$.

This allows to solve for the cost of work produced:

$$c_W = \frac{c_i[\dot{m}_i(e_i - e_e)] + c_Q\,\dot{Q}_i + \dot{Z}_T}{\dot{W}_e}$$

The reheat turbine case includes the simple turbine one : $Q_i = 0$

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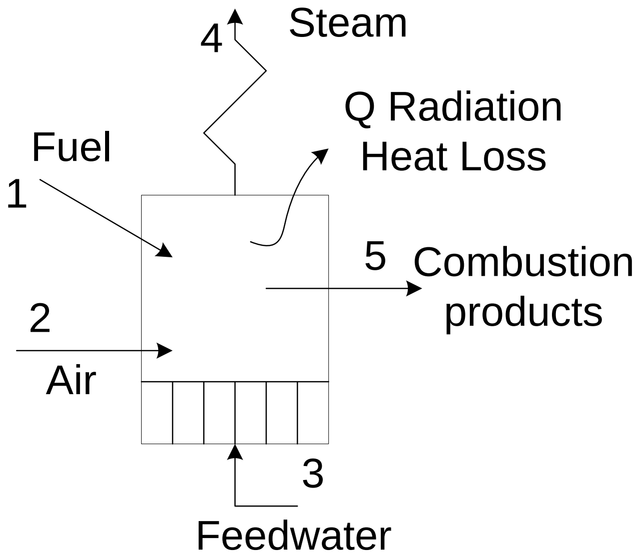
EEA Example 2 – Steam Generator



Referring to the Steam generator here represented:

$$\dot{C}_4 + \dot{C}_5 + \dot{C}_Q = \dot{C}_1 + \dot{C}_2 + \dot{C}_3 + \dot{Z}_{Boiler}$$

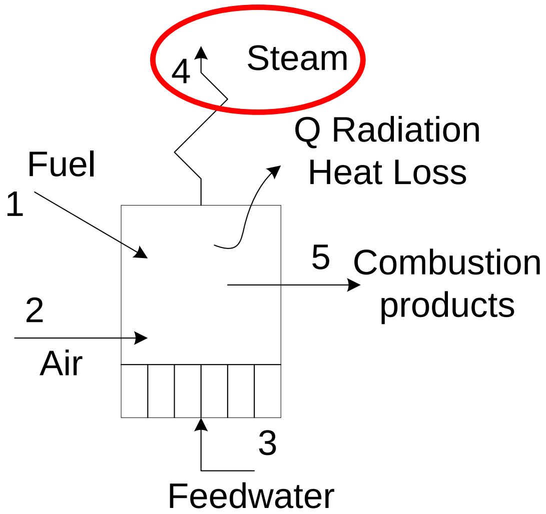
Introducing the cost per unit exergy:

$$c_4 \dot{E}_4 + c_5 \dot{E}_5 + c_Q \dot{E}_Q = c_1 \dot{E}_1 + c_2 \dot{E}_2 + c_3 \dot{E}_3 + \dot{Z}_{Boiler}$$

In this equation, the costs of inlet streams (fuel, air and feedwater) c_1, c_2, c_3 are known (either from market price, or from the solutions of components placed ahead of the steam generator); it is necessary to make realistic logical assumptions for the unit exit costs c_4, c_5, c_Q.

Boiler. ees

EEA Example 2 – Steam Generator



We are interested in the main product of the steam generator, which is steam (stream 4).

Streams Q and 5 represent exergy losses: namely, 5 is the steam generator sensible heat loss; while Q is the Radiative Loss.

It makes sense to consider the **cost of loss equal to the cost of fuel**[a] [€/MJ] necessary to have the component working (that is, the market cost of fuel):

$$c_5 = c_1 \qquad c_Q = c_1$$

[a] *This is a common assumption in exergo-economics.*
There is one alternative, that is, to consider zero the cost of the exergy loss.

EEA Example 2 – Steam Generator

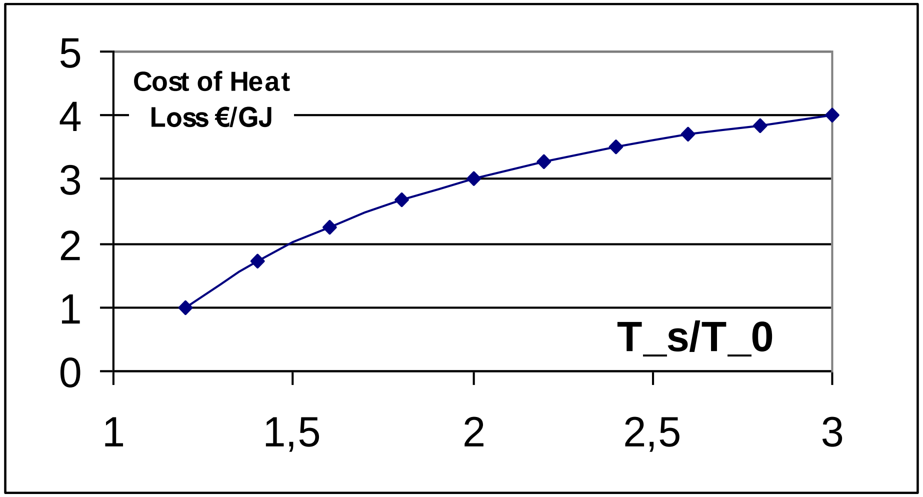
With these hypotheses on the cost of exergy losses, one can solve for the unit exergy cost of steam c_4:

$$c_4 = \frac{c_1\left(\dot{m}_1 e_1 - \dot{m}_5 e_5 - \dot{E}_Q\right) + c_2 \dot{m}_2 e_2 + c_3 \dot{m}_3 e_3 + \dot{Z}_{Boiler}}{\dot{m}_4 e_4}$$

The cost of the radiative (heat) loss is priced at the cost of heat-exergy $E_{Q:}$

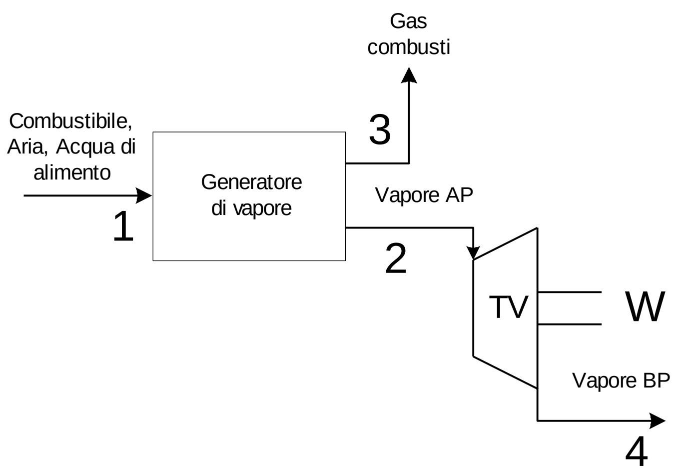
$$\dot{E}_Q = \dot{Q}\left(1 - \frac{T_0}{T_s}\right)$$

The idea is that the cost of heat loss should reflect the temperature level at which the heat loss is taking place.



This figure shows the cost of heat loss as a function of temperature Ts, starting from the fuel cost of natural gas at $c_1 = c_F = 6$ €/GJ.

Example 3 – CHP system (Backpressure steam turbine)



The CHP system example is taken from the textbook BMT[3], but it is completely reworked and is accompanied by a working EES program.

The steam generator is treated as a simplified system, considering only the cost of the fuel (disregarding that of the other inlet streams: air, feedwater).

The cost of the sensible heat loss (stream 3, hot combustion products) is neglected[b].

[b] *This is the alternative to pricing the loss at the cost of the fuel.*

[3]Bejan A, Tsatsaronis G, Moran M Thermal design and optimization. Wiley, 1996, New York

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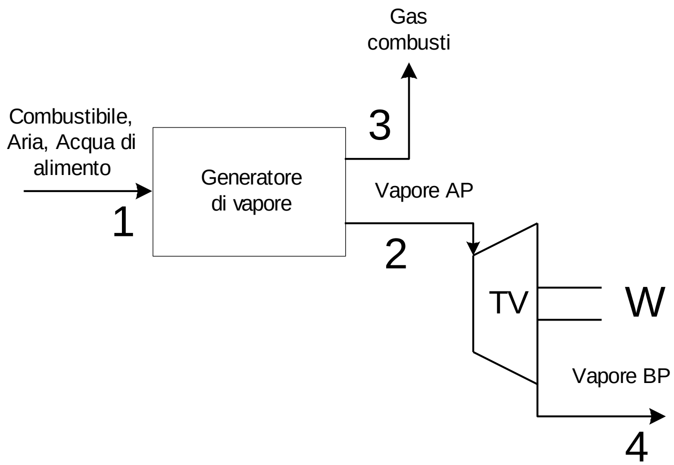
Example 3 – CHP system (Backpressure steam turbine)



The high pressure (point 2: 50 bar, 466,1°C) steam flow rate is given m_2 = 26,15 kg/s. The inlet flow of exergy (fuel) is 100 MW, at a cost of 4 €/GJ.

The steam generator destroys 60 MW of exergy.

The capital costs (including O&M) are estimated at $\mathbf{Z_b = 0{,}3}$ **€/s** for the steam generator and $\mathbf{Z_t = 0{,}2\ (W / 10)}$ €/s for the backpressure turbine.

W is the power of the turbine expressed in MW_e (ref. Size = 10 MW_e)

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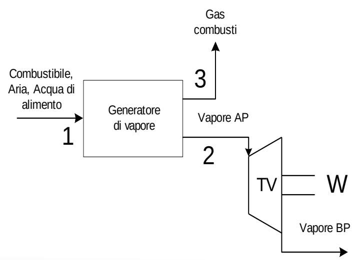
Example 3 – CHP system (Backpressure steam turbine)



The example considers the possibility of producing steam for the process at different pressures p_4, from 50 bars (no backpressure turbine $\eta_t = 0{,}8$, direct steam output) to 1 bar.

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Table 8.1 Thermodynamic[a] and cost[b] data for the turbine of Figure 8.2[c]

p_4 (bars)	T_4 (°C)	$(\dot{m}h_4)$ (MW)	$(\dot{m}s_4)$ (kW/K)	$\dot{W}$ (MW)	$\dot{E}_D$ (MW)	$\dot{E}_4$ (MW)	$\dot{Z}_t$ ($/s)	c_w ($/GJ)	c_4^* (¢/kg)
50	466.1	−329.909	271.682	0	0	35.000	0	0	2.677
40	435.8	−331.389	272.206	1.480	0.156	33.364	0.0030	24.135	2.552
30	398.4	−333.211	272.888	3.302	0.360	31.338	0.0066	24.179	2.397
20	349.0	−335.632	273.845	5.723	0.645	28.632	0.0114	24.246	2.190
9	261.9	−339.912	275.756	10.003	1.215	23.782	0.0200	24.435	1.819
5	205.2	−342.694	277.160	12.785	1.633	20.582	0.0256	24.555	1.574
2	128.3	−346.434	279.433	16.525	2.311	16.164	0.0330	24.797	1.236
1	99.6	−348.906	281.134	18.997	2.818	13.185	0.0380	24.997	1.008

1 p_4 [bar]	2 T_4 [C]	3 $h_{g;4}$ [kW]	4 $s_{g;4}$ [kW/K]	5 W [kW]	6 e_d [kW]	7 $e_{g;4}$ [kW]	8 h_4 [kJ/kg]	9 s_4 [kJ/kg-K]
50	466,1	-329910	271,4	0	0	34269	-12616	10,38
40	435,8	-331401	272	1490	152,4	32626	-12673	10,4
30	398,4	-333241	272,6	3330	348,5	30590	-12743	10,42
20	349	-335666	273,6	5756	632,5	27881	-12836	10,46
9	261,9	-339924	275,5	10013	1213	23042	-12998	10,54
5	205,2	-342682	277	12772	1645	19852	-13104	10,59
2	128,3	-346407	279,3	16497	2333	15439	-13246	10,68
1	100	-347654	284,3	17744	3821	12704	-13294	10,87

Example 3 – CHP system (Backpressure steam turbine)

Enthalpies and entropies for water are referenced to standard conditions (JANAF Tables); the following corrections apply with respect to steam tale values:

$h_J = h_{ST} - 15970$ [kJ/kg]

$s_J = s_{ST} + 3{,}509$ [kJ/(kgK)]

The turbine power output and exergy destruction are:

$W = m * (h_2 - h_4)$ $E_{dT} = m * T_0 * (s_2 - s_4)$

Example 3 – CHP system (Backpressure steam turbine)

Costing Equations:

$$c_2 \dot{E}_2 + c_3 \dot{E}_3 = c_1 \dot{E}_1 + \dot{Z}_{Boiler}$$ Steam Generator

$$c_4 \dot{E}_4 + c_W \dot{E}_W = c_2 \dot{E}_2 + \dot{Z}_{Turbine}$$ Turbine

Assuming $c_3 = 0$ (cost of sensible heat loss neglected); from the Steam Generator cost equation (with $p_4 = p_2 = 50$ bar):

$$c_2 = \frac{c_1 \dot{E}_1 + \dot{Z}_{Boiler}}{\dot{E}_2} = \frac{4*100/1000 + 0,3}{34,269/1000} = 20,43 \quad €/GJ$$

Example 3 – CHP system (Backpressure steam turbine)

Process steam is usually sold per unit mass; the c* cost per kg can be calculated multiplying by the specific exergy e_2 [GJ/kg]

$$c^*_2 = c_2 e_2 = c_2 \frac{\dot{E}_2}{\dot{m}} = 20{,}43 * \frac{34{,}269/1000}{26{,}151} = 2{,}677 \quad \text{c€/kg}$$

The turbine cost equation has two unknowns: c_4 (cost of low-pressure steam at turbine outlet and c_W cost of work. As in the first example, the purpose of a turbine is doing work.

This allows to consider constant the unit cost of exergy cost of the input and output streams, **$c_4 = c_2 = 20{,}43$ €/GJ** (calculated before). Then:

$$c_W = \frac{c_2\left(\dot{E}_2 - \dot{E}_4\right) + \dot{Z}_{Turbine}}{W} =$$

$$\frac{20{,}43*(34{,}269-23{,}042)/1000 + 0{,}02*10{,}013/10}{10{,}013/1000} = 24{,}9 \quad \text{€/GJ}$$

Example 3 – CHP system (Backpressure steam turbine)

The assumption **$c_4 = c_2 = 20{,}43$ €/GJ** does not mean that the cost of high-pressure and low-pressure steam is the same; in terms of mass, for the low-pressure steam:

$$c^*_4 = c_4 e_4 = \quad c_4 \frac{\dot{E}_4}{\dot{m}} = 20{,}43 * \frac{23{,}042/1000}{26{,}151} = 1{,}819 \qquad \text{c€/kg}$$

That is, low-pressure steam is less valuable than high-pressure steam steam; this happens because its exergy is lower.

This example addresses effectively one of the core problems of exergo-economic analysis, that is, attributing the correct cost to different products in case of a multi-purpose plant (power and heat).

Example 3 – CHP system (Backpressure steam turbine)

p_4 [bar]	T_4 [C]	$c_{star;4}$ [$/kg]	c_W [c$/GJ]	e_4 [kJ/kg]
40	435,8	0,02548	24,52	1248
30	398,4	0,02389	24,56	1170
20	349	0,02178	24,67	1066
9	261,9	0,018	24,9	881,1
5	205,2	0,01551	25,06	759,1
2	128,3	0,01206	25,32	590,4
1	100	0,009923	26,83	485,8

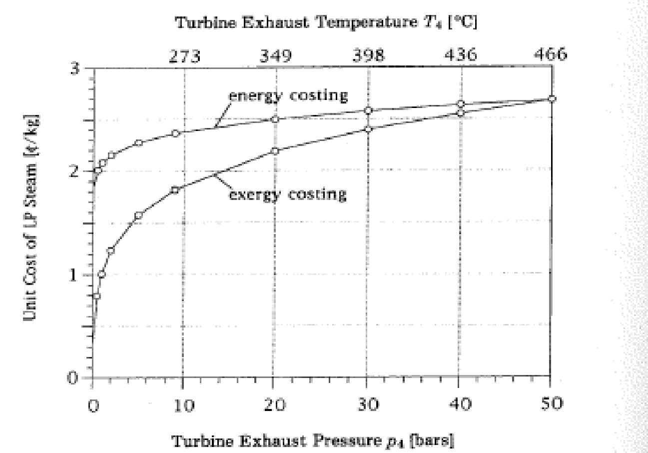
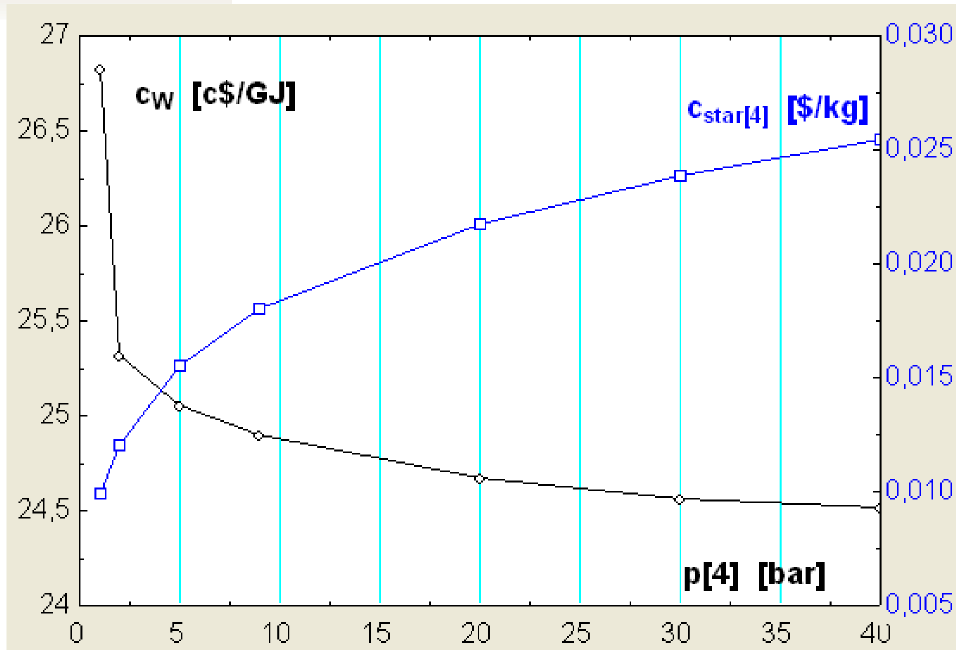


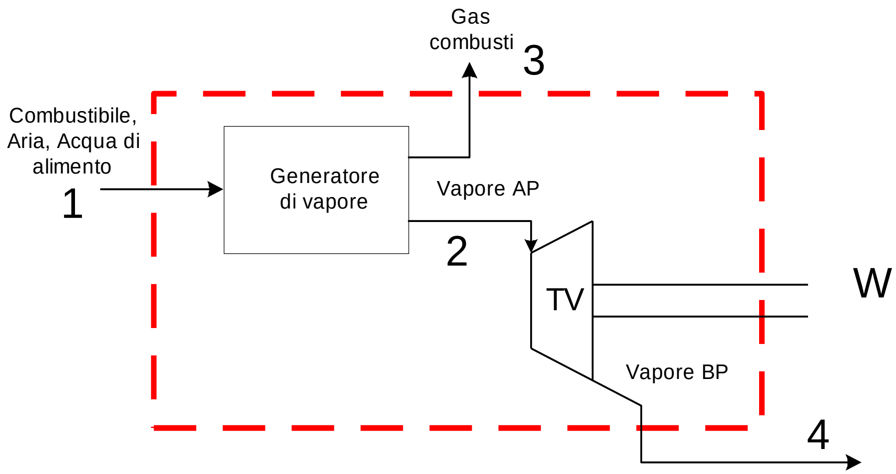
Figure 8.3 Cost of low-pressure steam per unit of mass, as a function of the turbine exhaust conditions for the system of Figure 8.2.

The parametric analysis screens the trend of the costs (power and low-pressure steam) with variable process pressure p_4.

Decreasing p_4, the cost of work is augmented and the cost of low-pressure steam decreases.



Example 3 – Effect of aggregation level - CHP system



The Aggregation Level should be set at the finest possible level possible for the analysis of the system.

Of course, detailed info about component cost should be available.

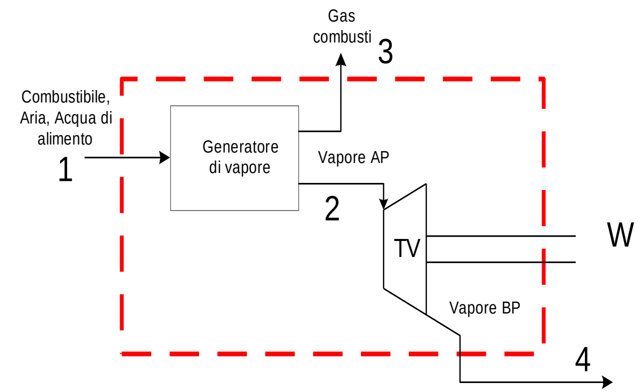
Let's say that there is no detailed info about the separate costs of the Steam generator and Turbine. The only info from cost reduction to unit time is that $\dot{Z}_{Boiler} + \dot{Z}_{Turbine}$ = 0,3+0,02 = 0,32 €/s (referring to a 1 MWe turbine). The costing equation with this limited info is:

$$c_4 \dot{E}_4 + c_W \dot{E}_W + c_3 \dot{E}_3 = c_1 \dot{E}_1 + \left(\dot{Z}_{Boiler} + \dot{Z}_{Turbine} \right)$$

$c_3 = 0$

Example 3 – Effect of aggregation level - CHP system

Without internal info about the turbine we cannot set $c_4 = c_2$ as before; the only possible way to solve the global cost equation is to take the plant cost as a whole, and attribute equal cost to the two products, work and low-pressure steam, that is: $c_4 = c_W$:



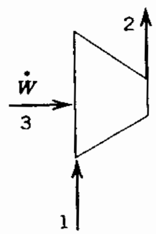
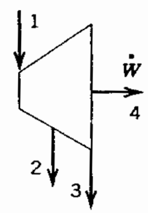
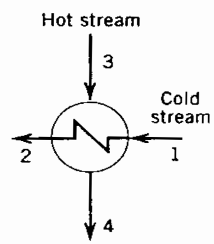
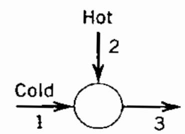
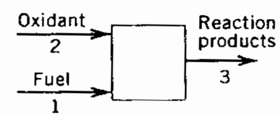
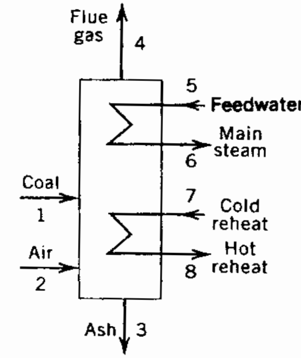
$$c_W = \quad c_4 = \frac{c_1 \dot{E}_1 + \left(\dot{Z}_{Boiler} + \dot{Z}_{Turbine}\right)}{\dot{E}_4 + \dot{W}} =$$

$$\frac{4*(100/1000)+(0{,}3+0{,}02)}{(23{,}042+10)/1000} = 21{,}3 \qquad \text{€/GJ}$$

This is quite different from the previous result, 24,4 €/GJ for work and 20,43 €/GJ for steam. Actually we are under-pricing one of the products (**work**) and over-pricing the other product (**steam**).

EEA - Auxiliary Equations for typical components

Table 8.3 Auxiliary thermoeconomic relations for selected components at steady-state operation when physical and chemical exergy are considered separately[a]

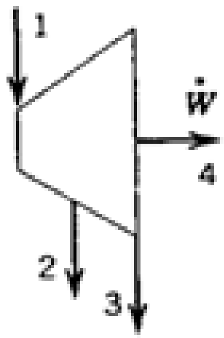
Component	Compressor, Pump, or Fan	Turbine or Expander	Heat Exchanger[b]	Mixing Unit	Gasifier or Combustion Chamber	Boiler
Schematic						
Auxiliary thermoeconomic relations	$c_2^{CH} = c_1^{CH}$	$c_2^{PH} = c_3^{PH} = c_1^{PH}$ $c_2^{CH} = c_3^{CH} = c_1^{CH}$	$c_4^{PH} = c_3^{PH}$ $c_4^{CH} = c_3^{CH}$ $c_2^{CH} = c_1^{CH}$	$c_3^{CH} = \frac{\dot C_1^{CH} + \dot C_2^{CH}}{\dot E_3^{CH}}$	$c_3^{CH} = c_3^{PH}$ (gasifier) $c_3^{CH} = c_1^{CH}$ (incomplete combustion) $c_3^{CH} = 0$ (complete combustion)	$c_6^{CH} = c_5^{CH}$, $c_8^{CH} = c_7^{CH}$ $c_3^{CH} = c_1^{CH}$, $c_4^{CH} = 0$ $\frac{\dot C_6^{PH} - \dot C_5^{PH}}{\dot E_6^{PH} - \dot E_5^{PH}} = \frac{\dot C_8^{PH} - \dot C_7^{PH}}{\dot E_8^{PH} - \dot E_7^{PH}}$ For c_3^{PH} and c_4^{PH} see Section 8.1.4 and Equations 8.14
	0	2	1	0	0	3
Variable calculated from cost balance	c_2^{PH}	c_w	c_2^{PH}	c_3^{PH}	c_3^{PH}	c_6^{PH} or c_8^{PH}

[a] The cost rates $\dot C_F$ and $\dot C_P$ for these components are defined in Table 8.2.

[b] These relations assume that the purpose of the heat exchanger is to heat the cold stream ($T_1 \geq T_0$). If the purpose of the heat exchanger is to provide cooling ($T_3 \leq T_0$), then the following relations should be used: $\dot C_P = \dot C_4 - \dot C_3$; $\dot C_F = \dot C_1 - \dot C_2$; $c_2^{PH} = c_1^{PH}$; $c_2^{CH} = c_1^{CH}$; and $c_4^{CH} = c_3^{CH}$. The variable c_4^{PH} is calculated from the cost balance.

A general rule is that a numer of **n-1** auxiliary equations are needed for a component with **n** outputs.

Steam turbine with extraction



$$\dot{C}_W + \dot{C}_2 + \dot{C}_3 = \dot{C}_1 + \dot{Z}_{Turbine}$$

$$c_W = \frac{c_1 \dot{E}_1 - c_2 \dot{E}_2 - c_3 \dot{E}_3 + \dot{Z}_{Turbine}}{\dot{W}}$$

N =3 (streams 2, 3 + W)

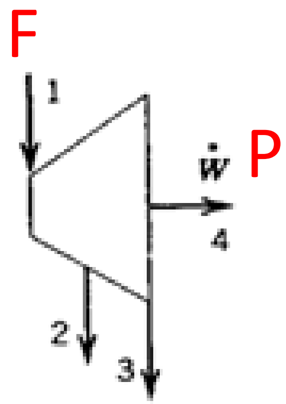
Auxiliary equations (the purpose of a turbine is producing work):

$c_2 = c_1$, $c_3 = c_1$ (constant cost per unit exergy)

$$c_W = \frac{c_1\left(\dot{E}_1 - \dot{E}_2 - \dot{E}_3\right) + \dot{Z}_{Turbine}}{\dot{W}}$$

Direct solution

Steam turbine with extraction – Costing exergy destruction



It is possible to use the turbine exergy balance to put in evidence the cost of exergy destruction:

$$W + E_D = (E_1 - E_2 - E_3)$$ Exergy Balance

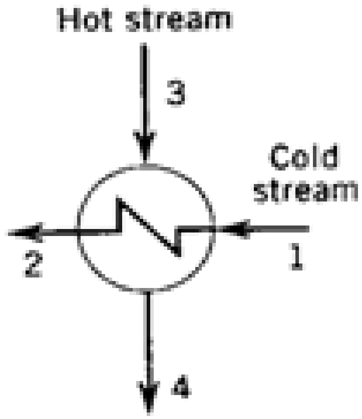
Direct solution

$$c_W = \frac{c_1\left(\dot{E}_1 - \dot{E}_2 - \dot{E}_3\right) + \dot{Z}_{Turbine}}{\dot{W}} = \frac{c_1\left(\dot{E}_D + \dot{W}\right) + \dot{Z}_{Turbine}}{\dot{W}}$$

$$c_W = c_1 + \frac{c_1 \dot{E}_D + \dot{Z}_{Turbine}}{\dot{W}}$$

The cost of work is represented by the cost of a "Fuel" stream c_1 + the Cost of Exergy Destruction (priced at the cost of fuel c_1) + the Capital Cost introduced by the turbine.

Surface Heat Exchangers



Surface Heat Exchangers are common relevant components.

We assume here perfect external insulation (no Exergy Loss; only heat transfer exrgy destruction); the Heat Exchanger operates above the reference temperature*.

The Cost Equation is:

$$\dot{C}_2 + \dot{C}_4 = \dot{C}_1 + \dot{C}_3 + \dot{Z}_{HeatExch}$$

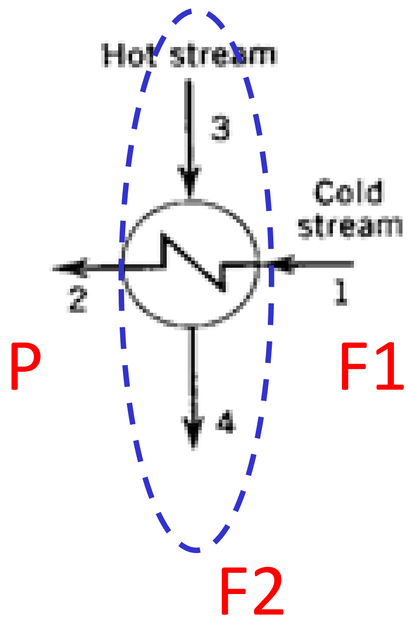
Which can be rearranged considering stream continuity:

$$\left(c_2 \dot{E}_2 - c_1 \dot{E}_1\right) = \dot{m}_2\left(c_2 e_2 - c_1 e_1\right) =$$

$$\left(c_3 \dot{E}_3 - c_4 \dot{E}_4\right) + \dot{Z}_{HeatExch} = \dot{m}_3\left(c_3 e_3 - c_4 e_4\right) + \dot{Z}_{HeatExch}$$

* Special treatment is necessary for heat exchangers operating below ambient temperature!

Surface Heat Exchanger – Heating the Cold Stream



$$\dot{m}_2(c_2 e_2 - c_1 e_1) = \dot{m}_3(c_3 e_3 - c_4 e_4) + \dot{Z}_{HeatExch}$$

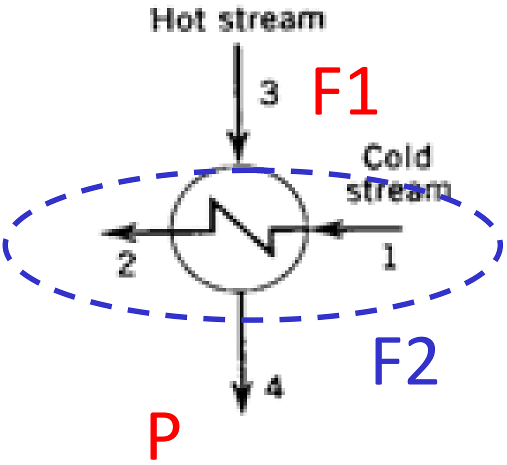
As n = 2, we need 1 additional equation. The solution depends on the purpose of the heat exchanger.

If the purpose of the HE is to heat the cold stream, we should assume that the cost of the Hot Stream is constant, $c_4 = c_3$. This allows to solve for the unknown c_2:

$$c_2 = \frac{c_1 \dot{E}_1 + c_3(\dot{E}_3 - \dot{E}_4) + \dot{Z}_{HeatExch}}{\dot{E}_2}$$

It appears that the HE has **1 Product** (**stream** 2), and uses **2 Fuel streams**: stream 1 (to be upgraded) + the decrease of exergy of the hot stream, $(\dot{E}_3 - \dot{E}_4)$; the third contribution is that of the HE Capital Cost.

Surface Heat Exchanger – Cooling the Hot Stream



$$\dot{m}_2\left(c_2\,e_2-c_1\,e_1\right) = \dot{m}_3\left(c_3\,e_3-c_4\,e_4\right)+\dot{Z}_{HeatExch}$$

As n = 2, we need 1 additional equation. The solution depends on the purpose of the heat exchanger.

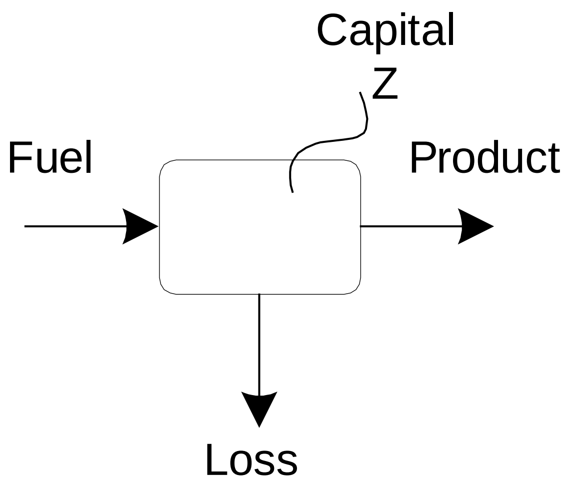
If the purpose of the HE is to cool the hot stream, we should assume that the cost of the Cold Stream is constant, $c_2 = c_1$. This allows to solve for the unknown c_4:

The solution can also be set using the HE exergy Destruction

$$c_4 = \frac{c_3\,\dot{E}_3+c_1\left(\dot{E}_2-\dot{E}_1\right)+\dot{Z}_{HeatExch}}{\dot{E}_4}$$

It appears that the HE has **1 Product** (**stream** 2), and uses **2 Fuel streams**: stream 3 (to be cooled) + the increase of exergy of the cold stream, $\left(\dot{E}_2-\dot{E}_1\right)$; the third contribution is that of the HE Capital Cost.

EEA - The Cost of Exergy Loss - Assumptions



From a System point of view, we can consider a component with an exergy Loss (dispersion of Exergy to the Environment). The cost balance is:

$$\dot{C}_{Pk} = \dot{C}_{Fk} - \dot{C}_{Lk} + \dot{Z}_k$$

Referring to unit cost of exergy: $$c_{Pk}\dot{E}_{Pk} = c_{Fk}\dot{E}_{Fk} - \dot{C}_{Lk} + \dot{Z}_k$$

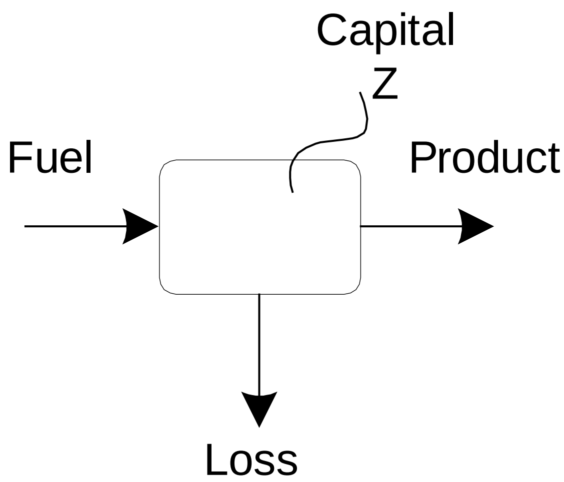
Assumption 1: $\dot{C}_{Lk} = 0$ $\quad c_{Lk} = 0$

Cost of exergy Loss = 0 (Loss attributed to system functionality)

This is a reasonable assumption when the purpose is to evaluate the final cost of a product as output of the system, or general optimization (minimization of product cost) at system level.

Examples: Condenser, Stack losses

EEA - The Cost of Exergy Loss - Assumptions



Assumption 2:

Cost of exergy Loss = Cost of Component Fuel stream

(Loss attributed to component)

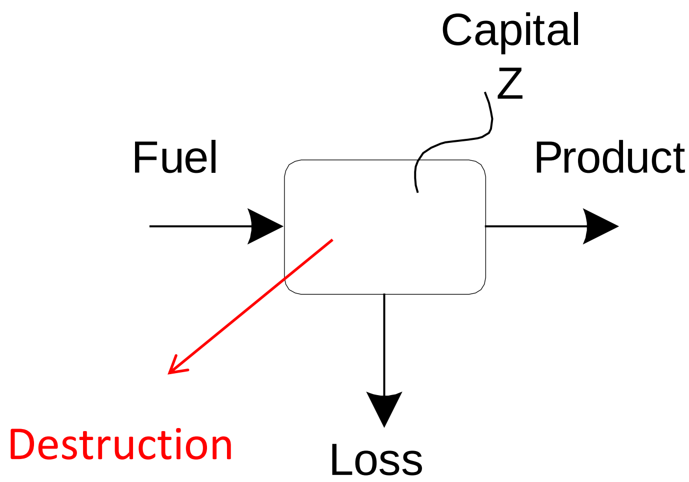
Examples: HE with defective insulation, Radiative Heat Loss in Steam Generator

$$\dot{C}_{Lk} = c_{Lk}\dot{E}_{Lk} = c_{Fk}\dot{E}_{Lk}$$

$$c_{Lk} = c_{Fk}$$

This is a reasonable assumption when the purpose is to improve the performance of a defective component; the loss – taking place in the component - is priced at the cost of the component fuel stream.

EEA - The Cost of Component Exergy Destruction



In general, a component has both an Exergy Destruction and an Exergy Loss.

The Component Exergy Balance is then :

$$\boxed{\dot{E}_{Fk} =} \; \dot{E}_{Pk} + \left(\dot{E}_{Lk} + \dot{E}_{Dk}\right)$$

The Component Cost Equation was:

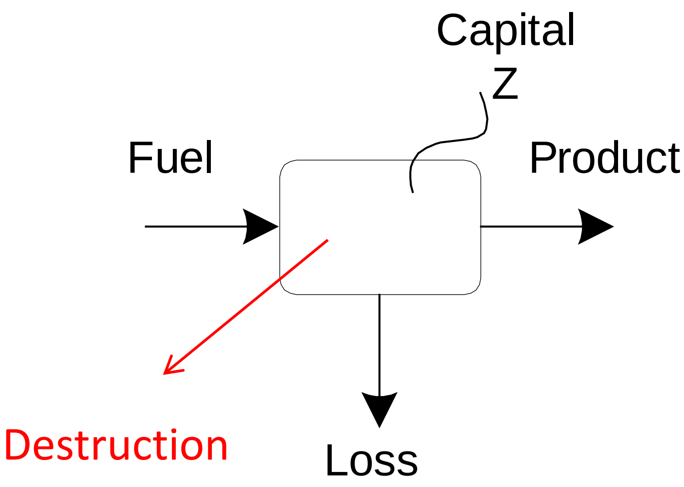
$$c_{Pk}\dot{E}_{Pk} = \boxed{c_{Fk}\dot{E}_{Fk}} - \dot{C}_{Lk} + \dot{Z}_k$$

Substituting the Component Exergy Balance in the Cost Equation:

$$c_{Pk}\dot{E}_{Pk} = c_{Fk}\dot{E}_{Pk} + \left(c_{Fk}\dot{E}_{Lk} - \dot{C}_{Lk}\right) + \dot{Z}_k + c_{Fk}\dot{E}_{Dk}$$

($\dot{E}_{fk}$ was eliminated through the Component Exergy Balance – Product-oriented approach)

EEA - The Cost of Component Exergy Destruction



$$c_{Pk}\dot{E}_{Pk} = c_{Fk}\dot{E}_{Pk} + \left(c_{Fk}\dot{E}_{Lk} - \dot{C}_{Lk}\right) + \dot{Z}_{k} + c_{Fk}\dot{E}_{Dk}$$

This equation shows that in EEA the Exergy Destruction **should be priced at the cost of the Fuel entering the component** k*:

$$c_{Dk} = c_{Fk}$$

Remember that for the Cost of Exergy Loss, two different assumptions are common:

$c_{Lk} = 0$ (system approach)

$c_{Lk} = c_{Fk}$ (component - progressive approach)

* In strict terms this is true only for “isolated” components, whose performance does not depend on that of other components. In this case, the Exergy destruction is called “Endogenous”

EEA - Component Performance Indicators

An important performance indicator is the relative cost increase across the component, r_k:

$$r_k = \frac{c_{p_k} - c_{f_k}}{c_{f_k}}$$

Using the Component Exergy Balance in the Cost Equation:

$$c_{Pk}\dot{E}_{Pk} = c_{Fk}\dot{E}_{Pk} + \left(c_{Fk}\dot{E}_{Lk} - \dot{C}_{Lk}\right) + \dot{Z}_k + c_{Fk}\dot{E}_{Dk}$$

And assuming (system level) $\dot{C}_{Lk} = 0$:

The relative cost increase r_k across the component is a function of the component cost, and of the costs of exergy destructions and exergy losses across the component:

$$r_k = \frac{c_{Fk}\left(\dot{E}_{Lk} + \dot{E}_{Dk}\right) + \dot{Z}_k}{c_{Fk}\dot{E}_{Pk}}$$

EEA - Component Performance Indicators

Another important performance indicator is the component exergy efficiency, ε_k:

$$\varepsilon_k = \frac{\dot{E}_{Pk}}{\dot{E}_{Fk}} = 1 - \frac{\dot{E}_{Dk} + \dot{E}_{Lk}}{\dot{E}_{Fk}}$$

Substituting for the group $\left(\dot{E}_{Lk} + \dot{E}_{Dk}\right)$ inside r_k:

$$r_k = \frac{c_{Fk}\left(\dot{E}_{Lk} + \dot{E}_{Dk}\right) + \dot{Z}_k}{c_{Fk}\dot{E}_{Pk}} \quad \Longrightarrow \quad r_k = \frac{1-\varepsilon_k}{\varepsilon_k} + \frac{Z_k}{c_{fk}\dot{E}_{p_k}}$$

The relative cost increase across the component r_k results to be a function of the exergetic efficiency ε_k of the component (including exergy destruction and loss), plus a contribution associated to the capital cost of the component.

(Product-based approach)

EEA - Component Performance Indicators

The Exergo-Economic Factor f_k is useful as a non-dimensional indicator, stating how much the capital cost is relevant with respect to the costs of exergy destructions and losses.

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{Fk}\left(\dot{E}_{Dk} + \dot{E}_{Lk}\right)}$$

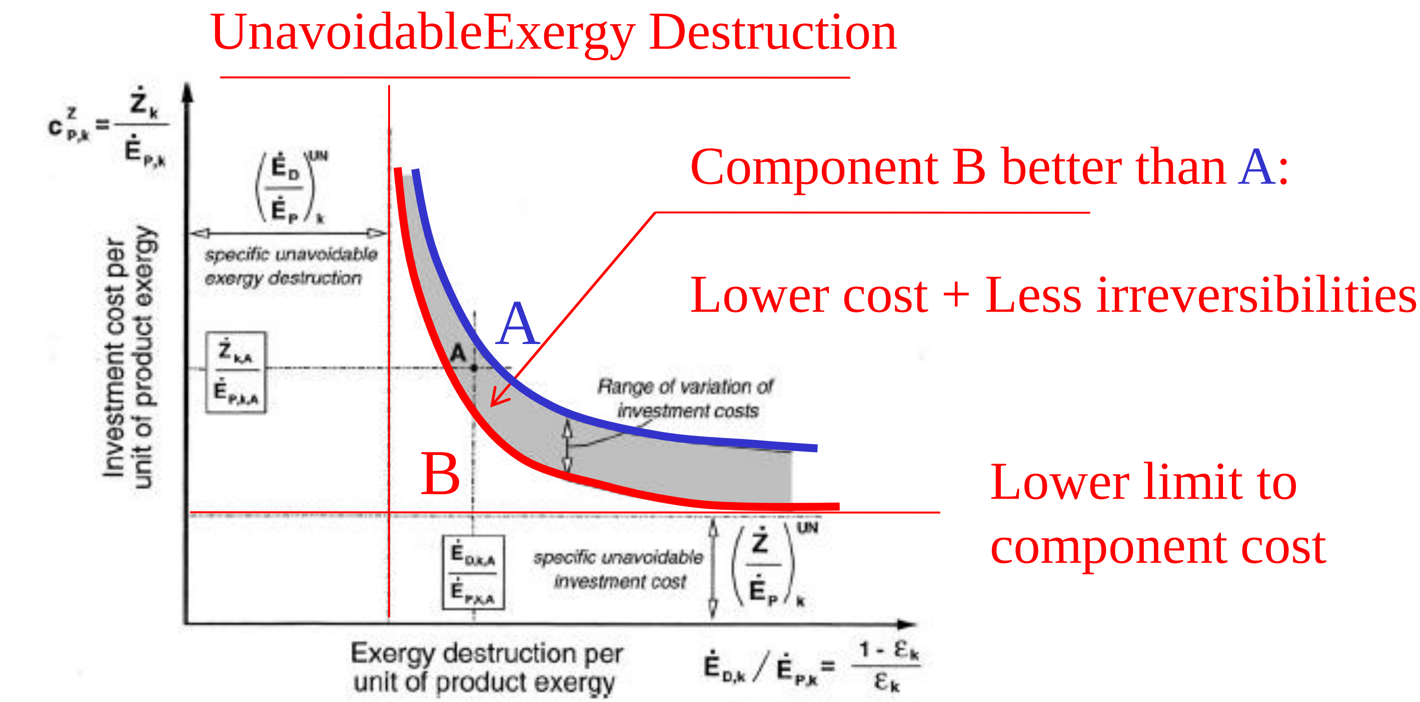
When analyizing the results of an EEA, it is recommended for system improvement to focus on components combining a low f_k and a low ε_k ; in these components, it is worth to apply a higher investment in order to reduce exergy destructions and losses at a low cost.

From a system point of view, however, one should also keep an eye at the size of the component exergy destruction y_k :

$$y_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$$

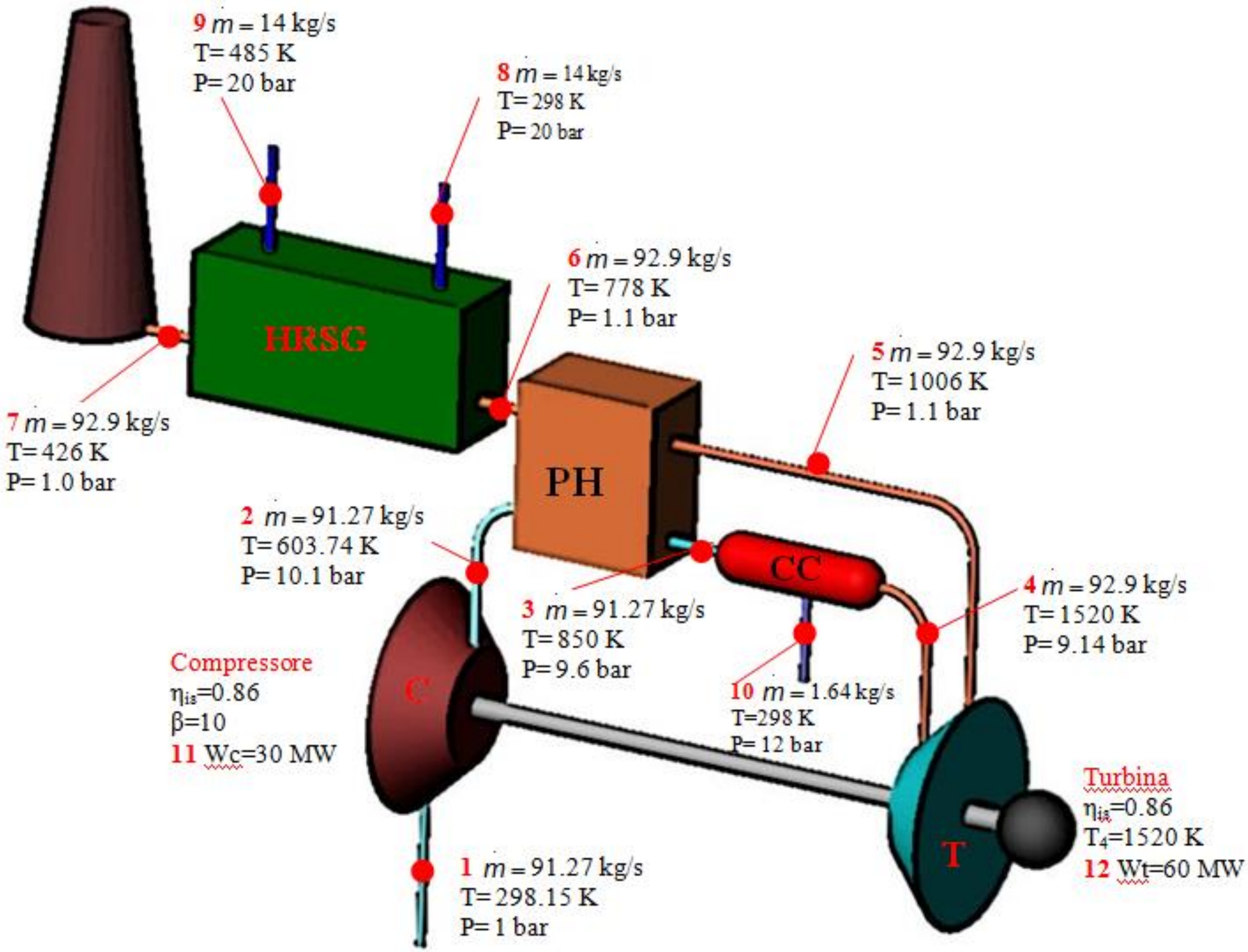
It is not important to increase the performance of components with small exergy destructions; one should focus on components responsible of large irreversibilities.

EEA – Capital cost vs. Exergy Destruction

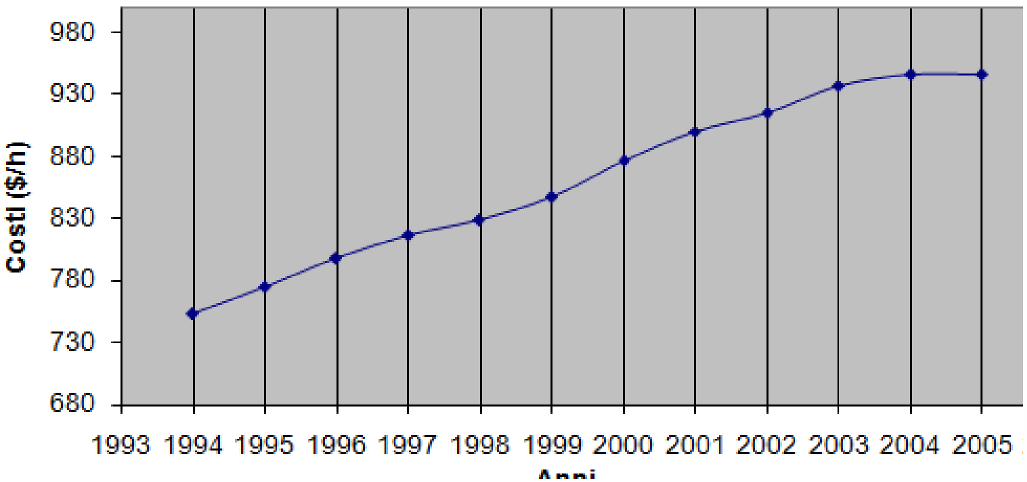


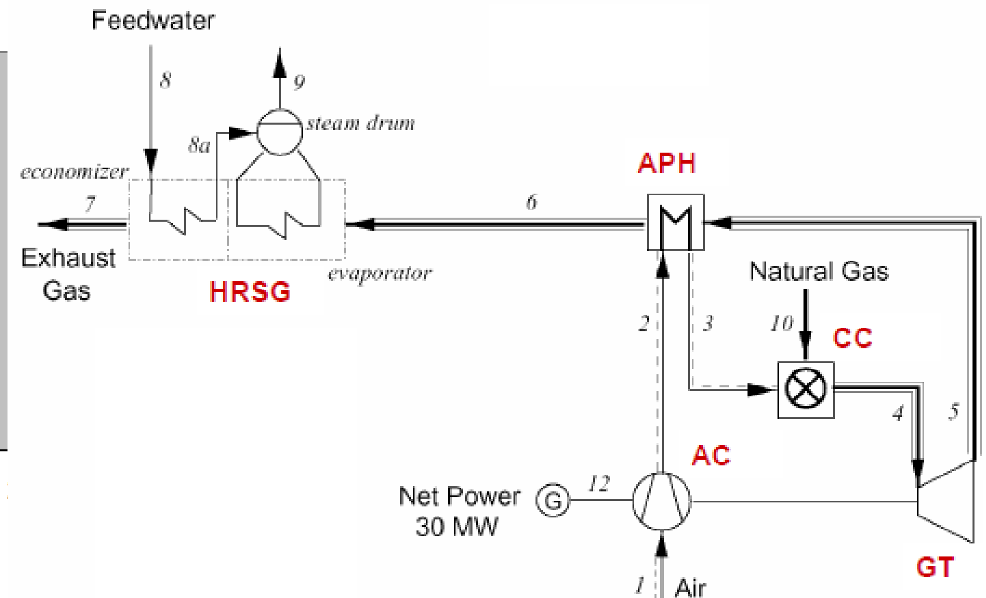
A breaktrough in technology is represented by a shift to a curve (B) with lower cost and better exergy performance than the base case (A).

EEA – CHP regenerative gas turbine test case (CGAM)



CGAM – Capital Costs





Levelization of cost with time (turbine)

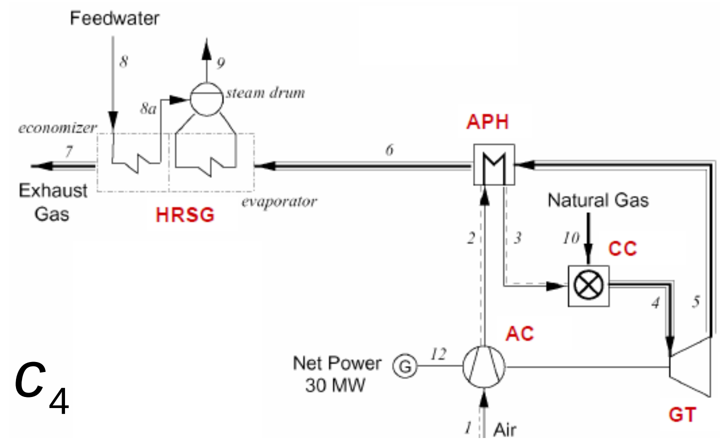
Z_c=945	[$/h]	Compressor
Z_t=945	[$/h]	Turbine
Z_{cc}=185	[$/h]	Combustion Chamber
Z_{ph}=237	[$/h]	Regenerative heat exchanger
Z_{hrsg}=331	[$/h]	Heat recovery steam generator

CGAM – Compressor + Turbine + Loop 1 (Mech)

Compressor AC:

$\dot{C}_1 + \dot{C}_{11} + \dot{Z}_c = \dot{C}_2$ $\dot{C}_1 = 0$ $\dot{C}_{11} = c_{11}\dot{E}_{11}$ $\dot{E}_{11} = \dot{W}_c = 30\text{ MW}$

No additional equations needed (n=1)



Turbine GT:

$\dot{C}_4 + \dot{Z}_t = \dot{C}_5 + \dot{C}_{11} + \dot{C}_{12}$

1 additional equations needed (n=2): $c_5 = c_4$

$$\frac{\dot{C}_4}{\dot{E}_4} = \frac{\dot{C}_5}{\dot{E}_5}$$

$c_{11} = c_{12}$ The compressor shaft work is provided by the turbine (to be determined, mechanical energy loop) $\frac{\dot{C}_{12}}{W_{12}} = \frac{\dot{C}_{11}}{W_{11}}$

CGAM – APH, CC + Loop2 (Heat recovery)

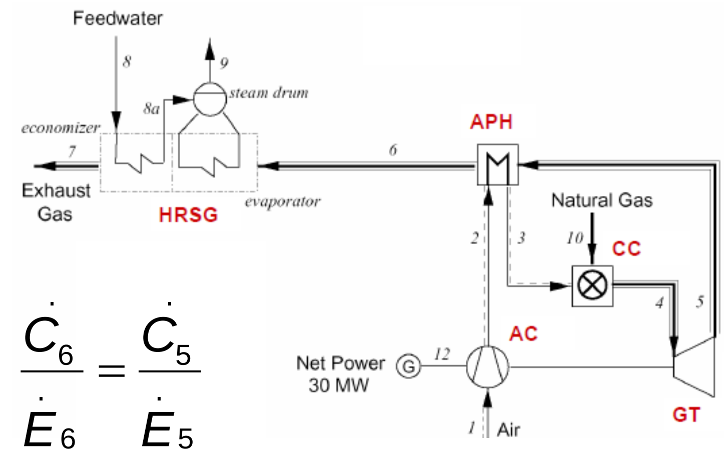
<u>Air Pre-Heater APH:</u>

$$\dot{C}_5 + \dot{C}_2 + \dot{Z}_{ph} = \dot{C}_3 + \dot{C}_6$$

1additional equation needed (n=2): $c_5 = c_6$ (constant cost of hot stream per unit exergy)

c_2 known from compressor outlet.

Unknown c_3.



$$\frac{\dot{C}_6}{\dot{E}_6} = \frac{\dot{C}_5}{\dot{E}_5}$$

<u>Combustion Chamber CC:</u>

$$\dot{C}_3 + \dot{C}_{10} + \dot{Z}_{cc} = \dot{C}_4$$

No additional equation needed (n=1):

c_3 known from APH outlet. Unknown c_4.

c_{10} is the cost of natural gas, €/GJ

Only now we can solve for: AC, GT, APH, CC.

4 unknowns, 4 equations.

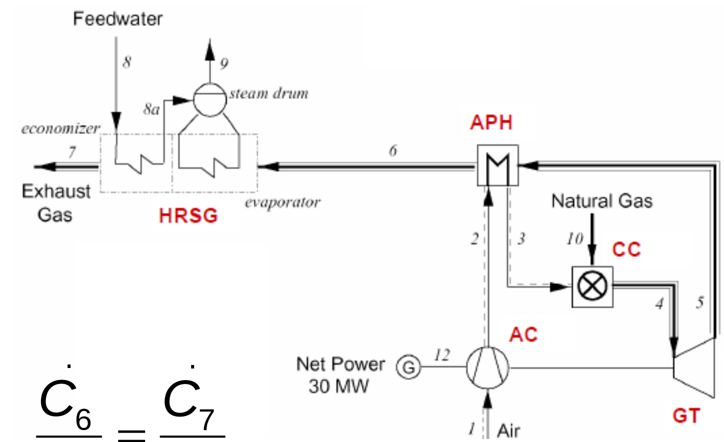
<u>Two loops</u>: mechanical energy, work stream 11-12; and stream 3 at APH exit.

CGAM – HRSG, Products (steam + electricity)

<ins>Heat Recovery Steam Generator (HRSG):</ins>

$$\dot{C}_6 + \dot{C}_8 + \dot{Z}_{hrsg} = \dot{C}_7 + \dot{C}_9$$

1additional equation needed (n=2): $c_7 = c_6$
(constant cost of hot stream per unit exergy)



$$\frac{\dot{C}_6}{\dot{E}_6} = \frac{\dot{C}_7}{\dot{E}_7}$$

The unknown is c_9, that is, the cost of the steam produced per unit exergy:

$$\dot{C}_9 = \dot{m}_9 e_9 c_9$$

c_8 is assumed here to be equal to zero (cost of recovered condensate stream)

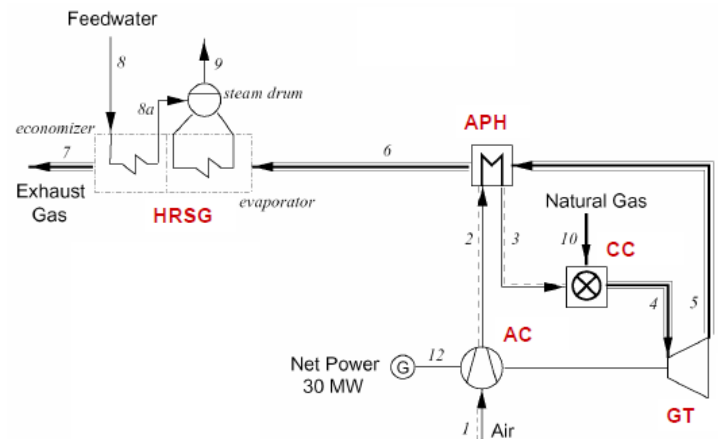
Rather, it is relevant to know c^*_9 in [€/kg]: $c_9^* = e_9 c_9$

The cost of electricity was already calculated as c_{12} [€/GJ]

CGAM – Streams, cost rates, unit exergy costs

Stream n°	E [MW]	C [$/h]	c [$/GJ]
1	0	0	0
2	27.54	3361.2	36.91
3	41.94	5122.8	33.93
4	101.45	7308	20.01
5	38.78	2794	20.01
6	21.75	1567.1	20.01
7	2.77	199.8	20.01
8	0.062	0	0
9	12.81	1695.6	36.83
10	84.99	2100.2	6.864
11	29.66	2701	25.42
12	30	2745.2	25.42

Stream n. 7 is the Stack Exergy Loss. Here it is priced at the cost of the fuel ($c_7=c_6=c_5=c_4$).



CGAM – EEA Standard Results

	ε (%)	E_D (MW)	c_f ($/GJ)	c_p ($/GJ)	C_D ($/h)	Z ($/h)	r (%)	f (%)
CC	79.9	**25.5**	6.84	20.0	**630**	185	12.6	**11.9**
Turb	95.2	3.01	20.0	**25.4**	217	945	27.0	**81.3**
Comp	92.9	2.10	25.4	36.9	194	945	45.2	**83.07**
HRSG	**67.2**	6.22	20.0	**36.8**	**449**	331	**84.0**	**42.4**
PH	84.6	2.63	20.0	33.9	189	237	69.6	**55.6**

1 GJ = 277,8 kWh

The result is a cost of electricity of c_{12} = **25,4 $/GJ**, that is: **9,1 c$/kWh**; and for steam, c_9 = **36,8 $/GJ, or** c^*_9 = **0,0337 $/kg**. ($e_9 = E_9/m_9$ = 12810/14 = 915 kJ/kg).

The Largest Exergy Destruction E_D = 25,5 MW is in the CC, with a large cost C_D = 630 $/h. The low f_{CC} = 11.9% indicates that the cost of the exergy destruction dominates over the capital cost.

The second largest E_D = 6,22 MW is in the HRSG, with a large C_D = 449 $/h and a relatively low f_{HRSG} = 42,4%. The HRSG also has the largest cost increase r_{HRSG} = 84% (product/fuel). Indeed the HRSG is not well matched from the point of view of hot gas/steam temperature profile.

CGAM – Official Results – EEA - Streams

Exergoeconomic Analysis – Base Case

Mass flow rate, temperature, pressure, exergy rate, and cost data for the streams

State	Stream	Mass flow rate, $\dot{m}$ [kg/s]	Tempe-rature, T [K]	Pressure, p [bar]	Exergy flow rate, $\dot{E}$ [MW]	Cost flow rate, $\dot{C}$ [$/h]	Cost per Exergy Unit, c [$/GJ]
1	Air	91.28	298.1	1.01	0.000	0	0
2	Air	91.28	603.7	10.13	27.538	2756	27.80
3	Air	91.28	850.0	9.62	41.938	3835	25340
4	Combustion products	92.92	1520.0	9.14	101.454	5301	14.51
5	Combustion products	92.92	1006.2	1.10	38.782	2026	14.51
6	Combustion products	92.92	779.8	1.07	21.752	1137	1451
7	Combustion products	92.92	426.9	1.01	2.773	145	14.51
8	Water	14.00	298.1	20.00	0.062	0	0
9	Water	14.00	485.6	20.00	12.810	1256	27.23
10	Methane	1.64	298.1	12.00	84.994	1398	4.57
11	Power to air compressor	-	-	-	29.662	2003	18.76
12	Net power	-	-	-	30.000	2026	18.76

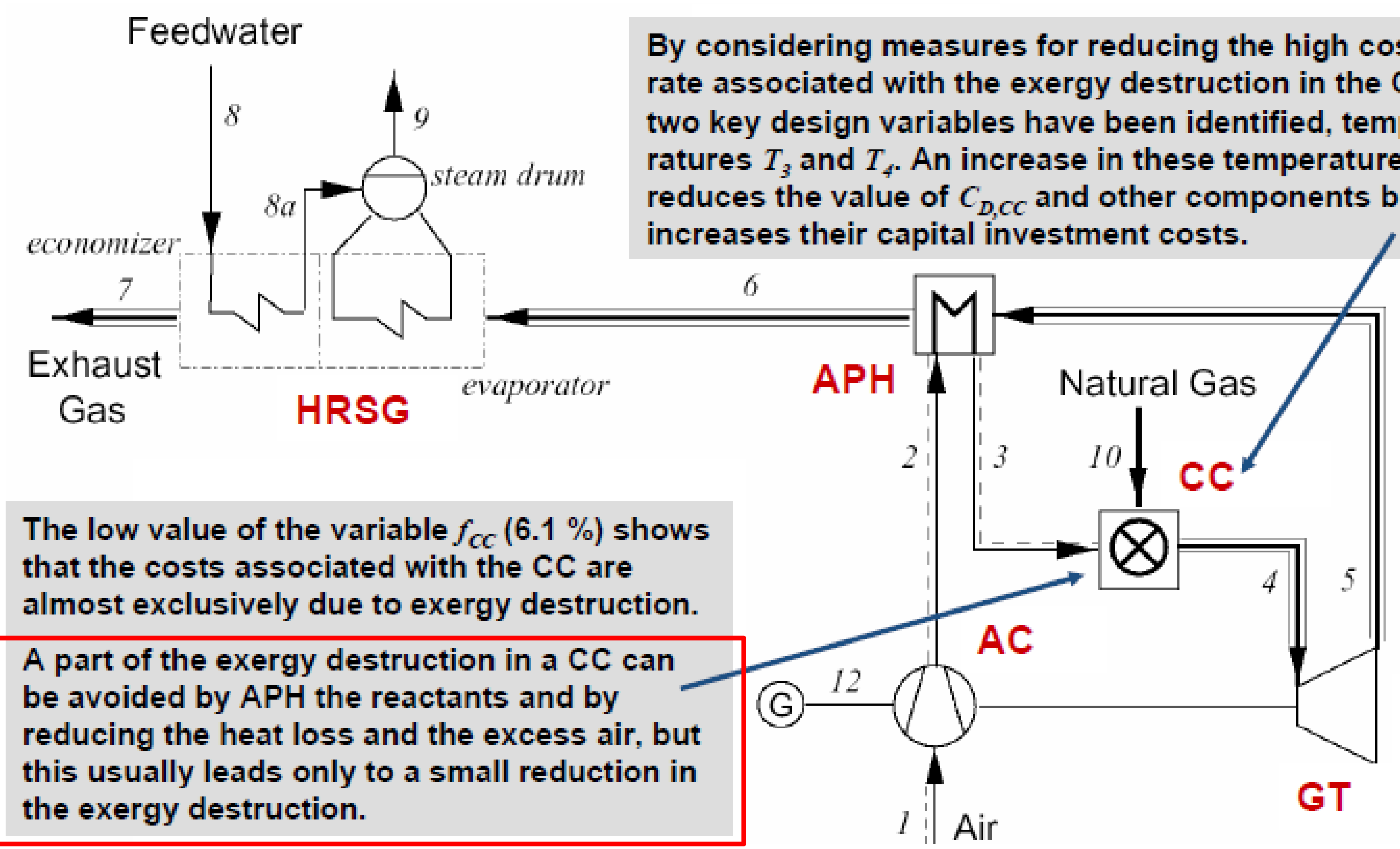
CGAM – Official Results – EEA - Components

Compo-nent	PEC [10^6\$]	ε [%]	$\dot{E}$ [MW]	y_D [%]	c_F [\$/GJ]	c_P [\$/GJ]	$\dot{C}_D$ [\$/GJ]	$\dot{Z}$ [\$/GJ]	$\dot{C}_D + \dot{Z}$ [\$/GJ]	r [%]	f [%]
Combustion Chamber	0.34	80.37	25.48	29.98	11.45	14.51	1050	68	1118	26.7	6.1
Gas Turbine	3.74	95.20	3.01	3.54	14.51	18.76	157	753	910	29.2	82.7
Air Compressor	3.73	92.84	2.12	2.50	18.76	27.80	143	753	896	48.2	84.0
HRSG	1.31	67.17	6.23	7.33	14.51	27.36	326	264	590	88.5	44.8
Air Preheater	0.94	84.58	2.63	3.09	14.51	20.81	137	189	326	43.4	57.9

For the overall plant: $C_{P,tot}$=\$3617/h and $C_{L,tot}$=C_7= \$145/h.

The *Combustion Chamber*, the *Gas Turbine*, and the *Air Compressor* have the highest values of the sum (Z_k + $C_{D,k}$) and are, therefore, the most important components from the thermoeconomic viewpoint.

CGAM – Official Results – EEA – Combustion Chamber



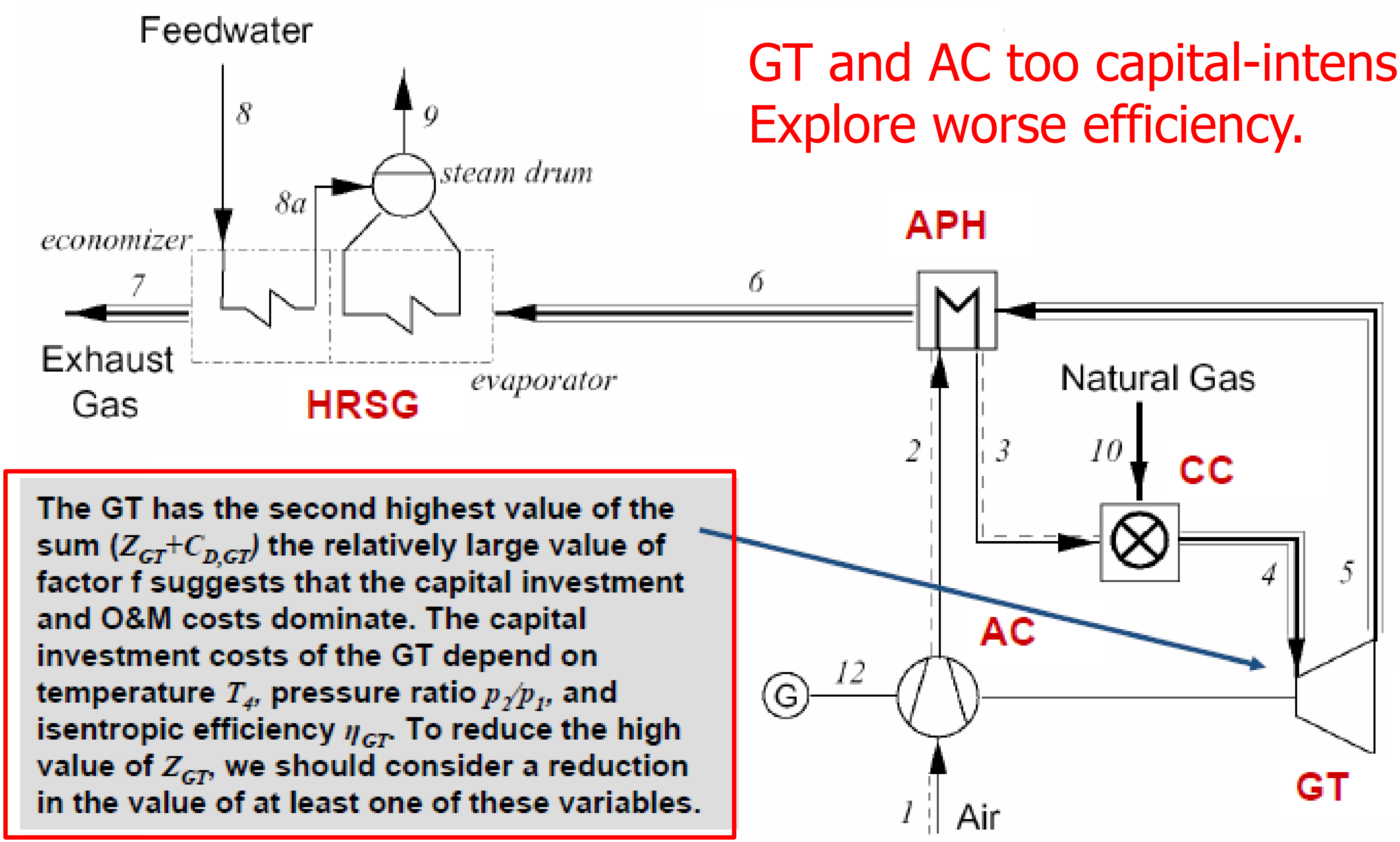
By considering measures for reducing the high cost rate associated with the exergy destruction in the CC, two key design variables have been identified, temperatures T_3 and T_4. An increase in these temperatures reduces the value of $C_{D,CC}$ and other components but increases their capital investment costs.

The low value of the variable f_{CC} (6.1 %) shows that the costs associated with the CC are almost exclusively due to exergy destruction.

A part of the exergy destruction in a CC can be avoided by APH the reactants and by reducing the heat loss and the excess air, but this usually leads only to a small reduction in the exergy destruction.

CGAM – Official Results – EEA – Turbine

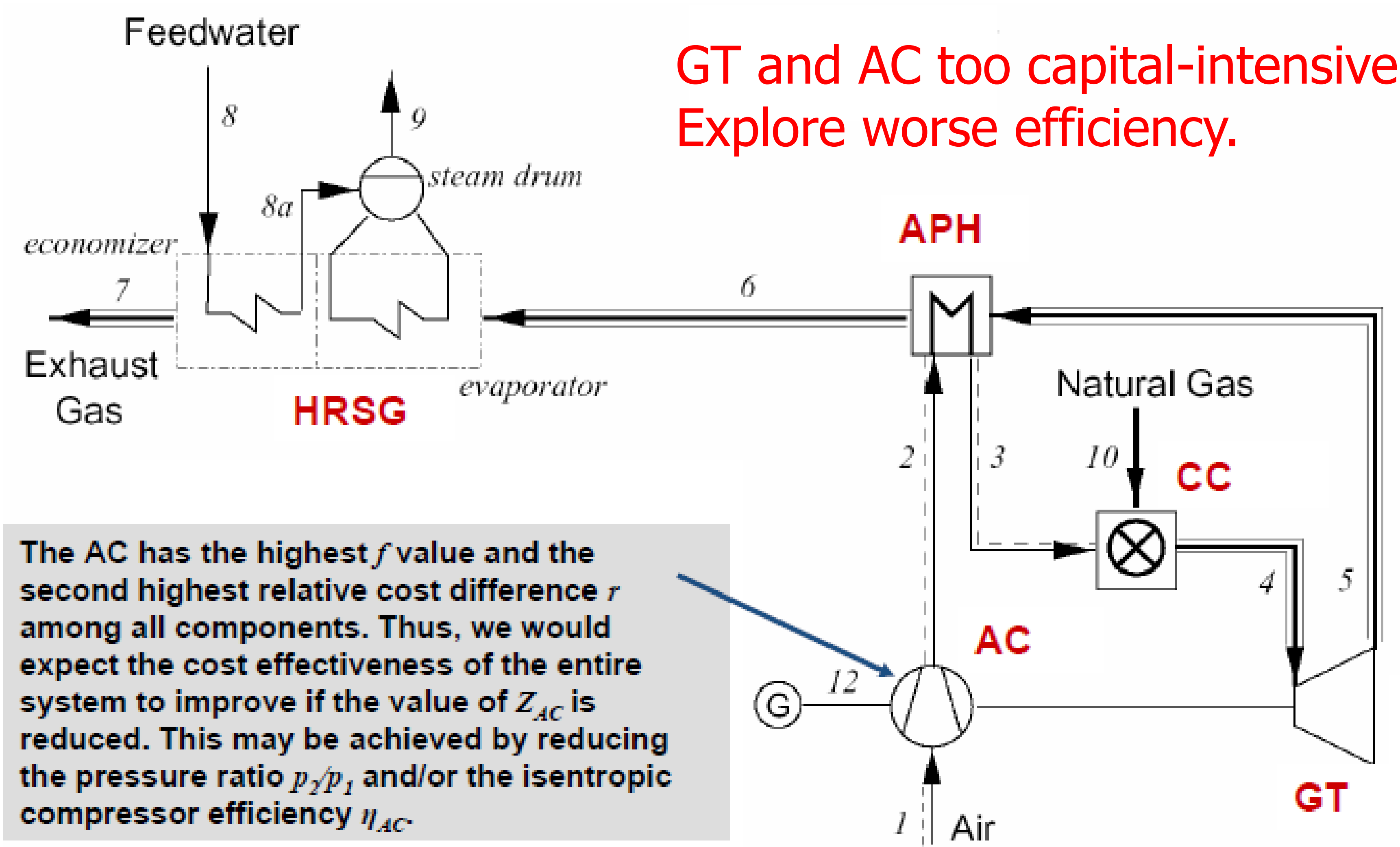
GT and AC too capital-intensive.
Explore worse efficiency.



The GT has the second highest value of the sum ($Z_{GT}+C_{D,GT}$) the relatively large value of factor f suggests that the capital investment and O&M costs dominate. The capital investment costs of the GT depend on temperature T_4, pressure ratio p_2/p_1, and isentropic efficiency η_{GT}. To reduce the high value of Z_{GT}, we should consider a reduction in the value of at least one of these variables.

CGAM – Official Results – EEA – Compressor

GT and AC too capital-intensive.
Explore worse efficiency.



The AC has the highest f value and the second highest relative cost difference r among all components. Thus, we would expect the cost effectiveness of the entire system to improve if the value of Z_{AC} is reduced. This may be achieved by reducing the pressure ratio p_2/p_1 and/or the isentropic compressor efficiency η_{AC}.

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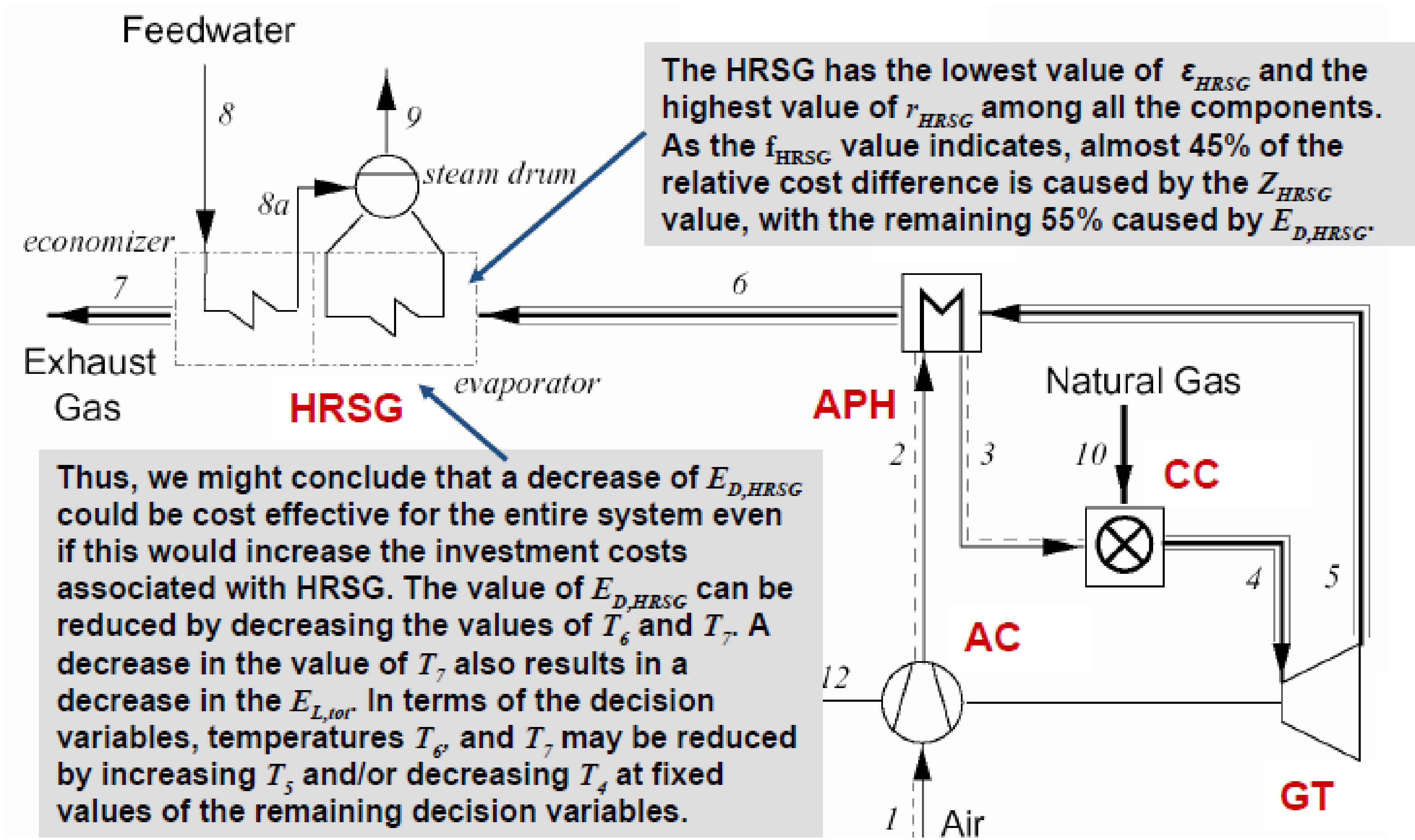
CGAM – Official Results – EEA –HRSG



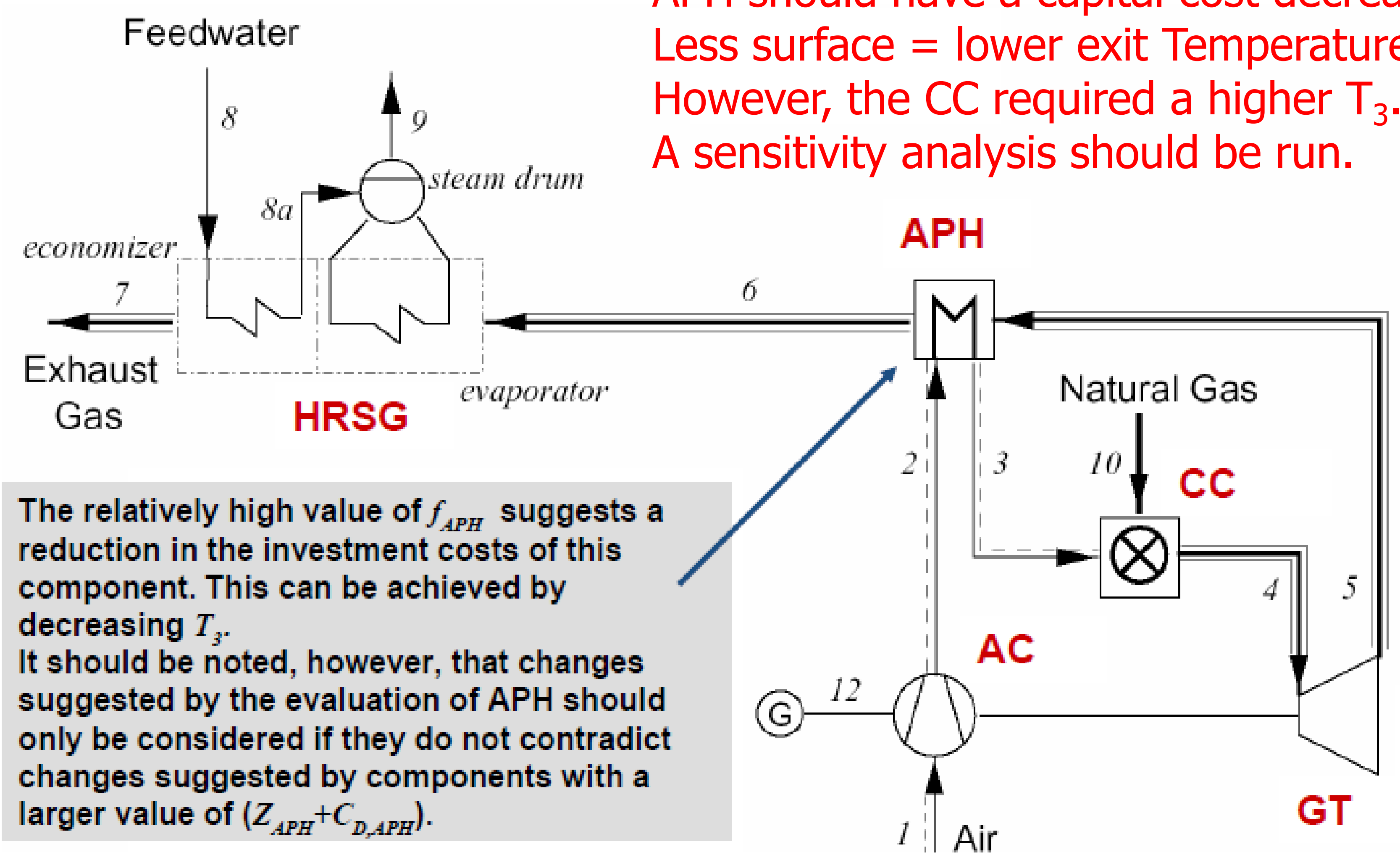
The HRSG has the lowest value of ε_{HRSG} and the highest value of r_{HRSG} among all the components. As the f_{HRSG} value indicates, almost 45% of the relative cost difference is caused by the Z_{HRSG} value, with the remaining 55% caused by $E_{D,HRSG}$.

Thus, we might conclude that a decrease of $E_{D,HRSG}$ could be cost effective for the entire system even if this would increase the investment costs associated with HRSG. The value of $E_{D,HRSG}$ can be reduced by decreasing the values of T_6 and T_7. A decrease in the value of T_7 also results in a decrease in the $E_{L,tot}$. In terms of the decision variables, temperatures T_6, and T_7 may be reduced by increasing T_5 and/or decreasing T_4 at fixed values of the remaining decision variables.

HRSG deserves some capital cost increase (surface, DT pinch).
Its performance is affected by that of other components (Turbine)

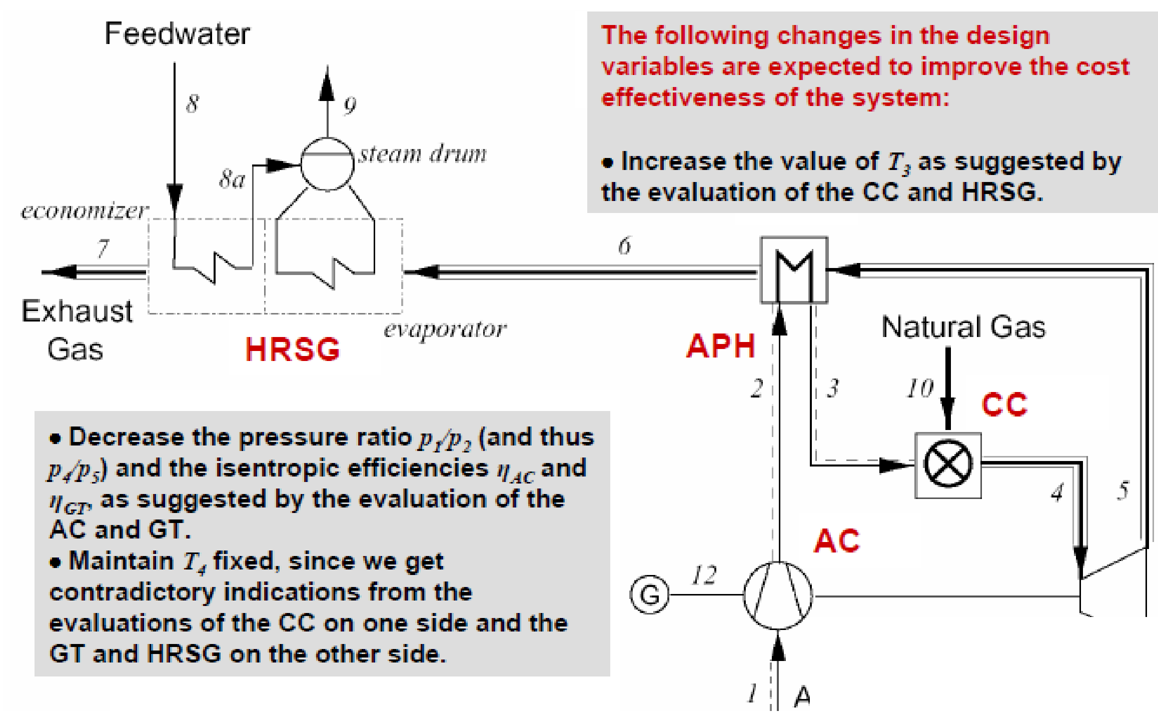
CGAM – Official Results – EEA – APH

APH should have a capital cost decrease.
Less surface = lower exit Temperature T_3.
However, the CC required a higher T_3.
A sensitivity analysis should be run.



The relatively high value of f_{APH} suggests a reduction in the investment costs of this component. This can be achieved by decreasing T_3.
It should be noted, however, that changes suggested by the evaluation of APH should only be considered if they do not contradict changes suggested by components with a larger value of $(Z_{APH}+C_{D,APH})$.

CGAM – EEA - Official Results – Improvement



The following changes in the design variables are expected to improve the cost effectiveness of the system:

- Increase the value of T_3 as suggested by the evaluation of the CC and HRSG.

- Decrease the pressure ratio p_1/p_2 (and thus p_4/p_5) and the isentropic efficiencies η_{AC} and η_{GT}, as suggested by the evaluation of the AC and GT.
- Maintain T_4 fixed, since we get contradictory indications from the evaluations of the CC on one side and the GT and HRSG on the other side.

Base Case

$p_1 / p_2 = 10$	$\eta_{ACT} = 0.86$	$\eta_{GT} = 0.86$	$T_3 = 850\ K$	$T_4 = 1520\ K$
↓	↓	↓	↓	
$p_1 / p_2 = 9$	$\eta_{ACT} = 0.85$	$\eta_{GT} = 0.85$	$T_3 = 870\ K$	$T_4 = 1520\ K$

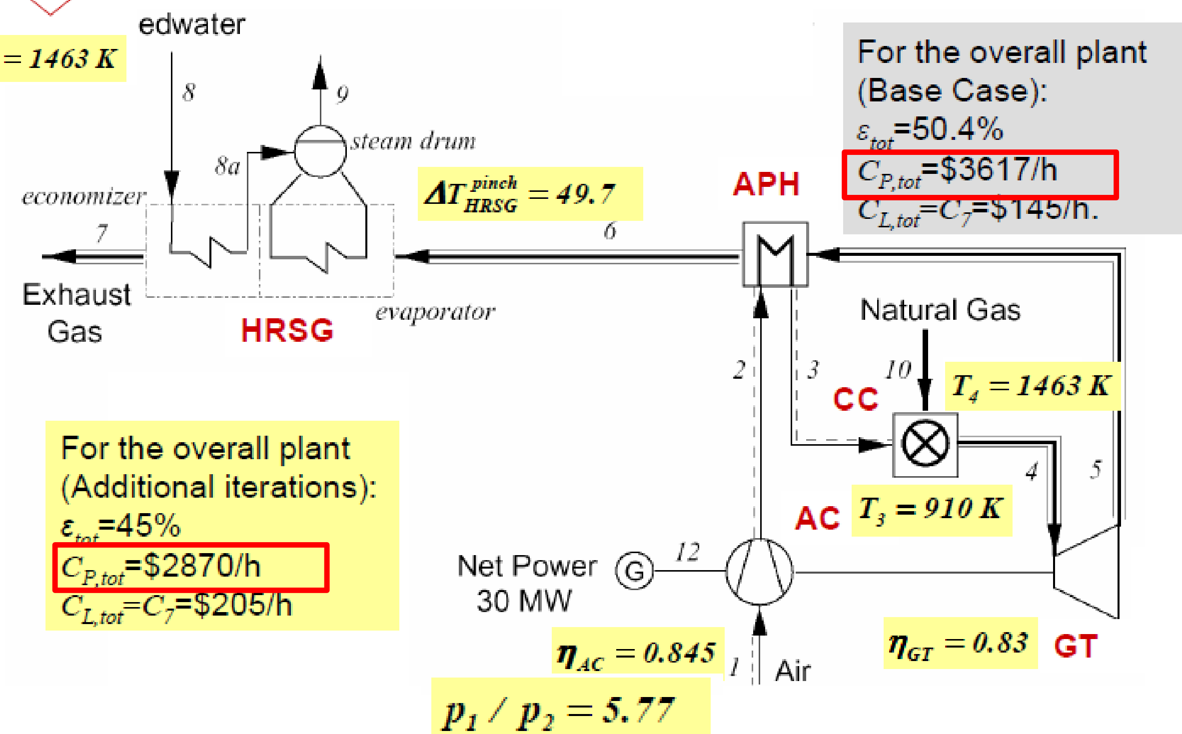
First iteration

CGAM – EEA - Official Results – Optimization

Base Case	$p_1/p_2 = 10$	$\eta_{AC} = 0.86$	$\eta_{GT} = 0.86$	$T_3 = 850\ K$	$T_4 = 1520\ K$
First iteration	$p_1/p_2 = 9$	$\eta_{AC} = 0.85$	$\eta_{GT} = 0.85$	$T_3 = 870\ K$	$T_4 = 1520\ K$
Second iteration	$p_1/p_2 = 7$	$\eta_{AC} = 0.83$	$\eta_{GT} = 0.83$	$T_3 = 910\ K$	$T_4 = 1480\ K$
Additional iterations	$p_1/p_2 = 5.77$	$\eta_{AC} = 0.845$	$\eta_{GT} = 0.83$	$T_3 = 910\ K$	$T_4 = 1463\ K$

Beware: comparisons and evaluation of Z should be done with politropic efficiencies rather than isentropic, when considering variable pressure ratio…!

This is not accounted for…

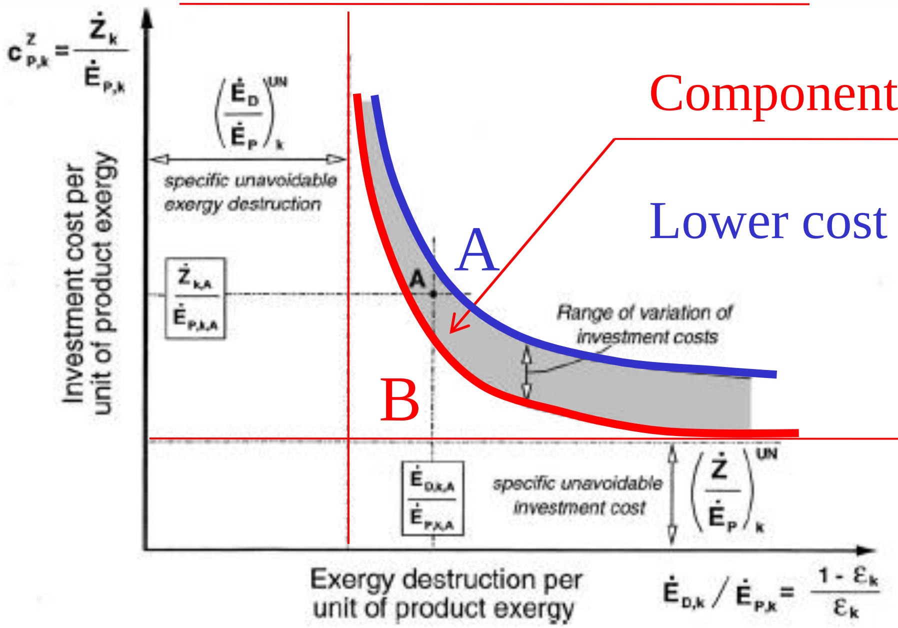


Advanced Exergoeconomic Analysis – Unavoidable ED - IC

Lower Limit
Unavoidable **Exergy Destruction ED**

Component B better than A:

Lower cost + Less irreversibilities



Lower limit to component
Investment Cost IC

What is Unavoidable…?

In terms of…

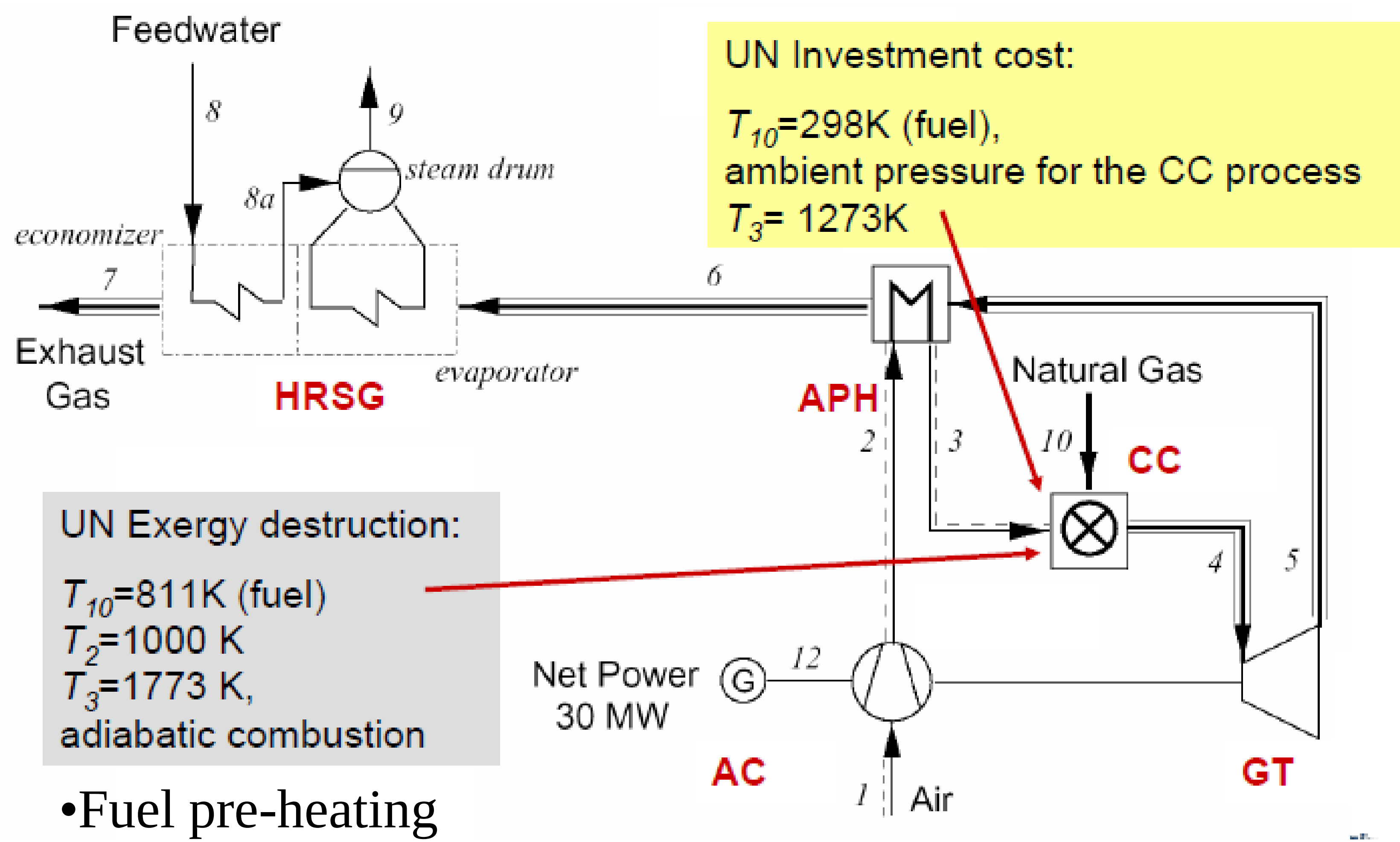
A) Exergy Destruction **ED** ….?

B) Investment cost **IC** ….?

…for each component…?

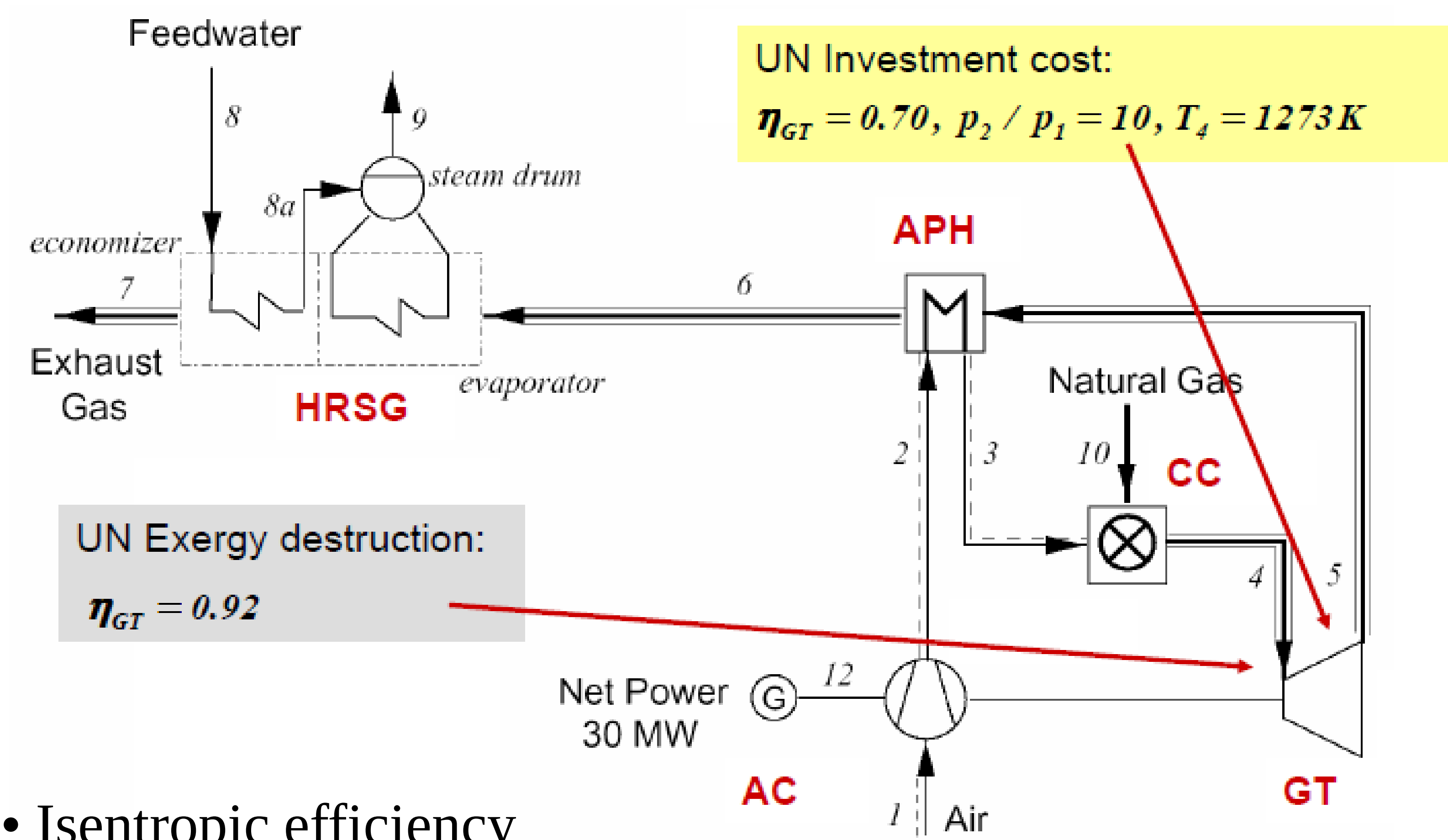
CGAM AEA Example

CGAM – AEA – Unavoidable – ED – IC - CC



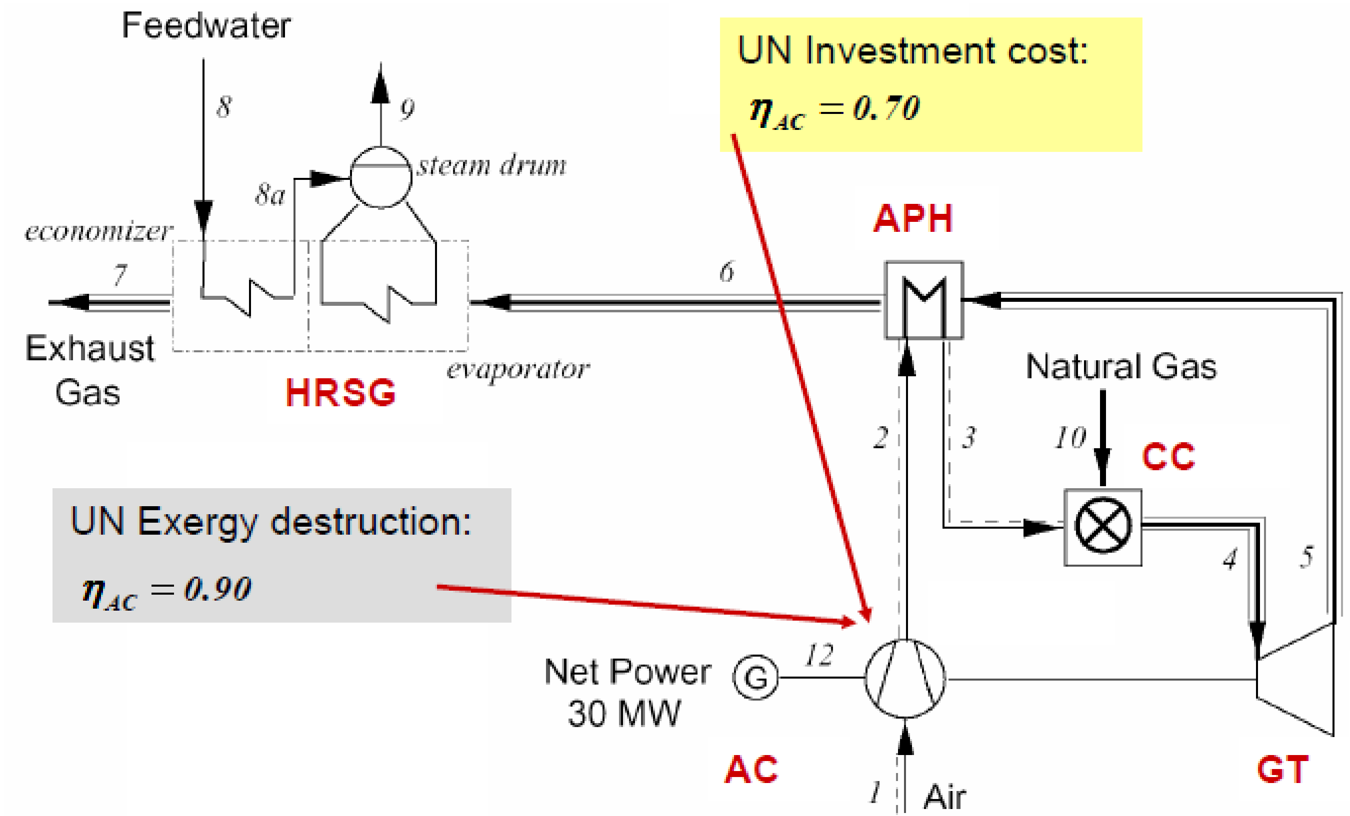
- Fuel pre-heating
- Air Pre-Heating
- Material constraints

CGAM – AEA – Unavoidable – ED – IC - GT



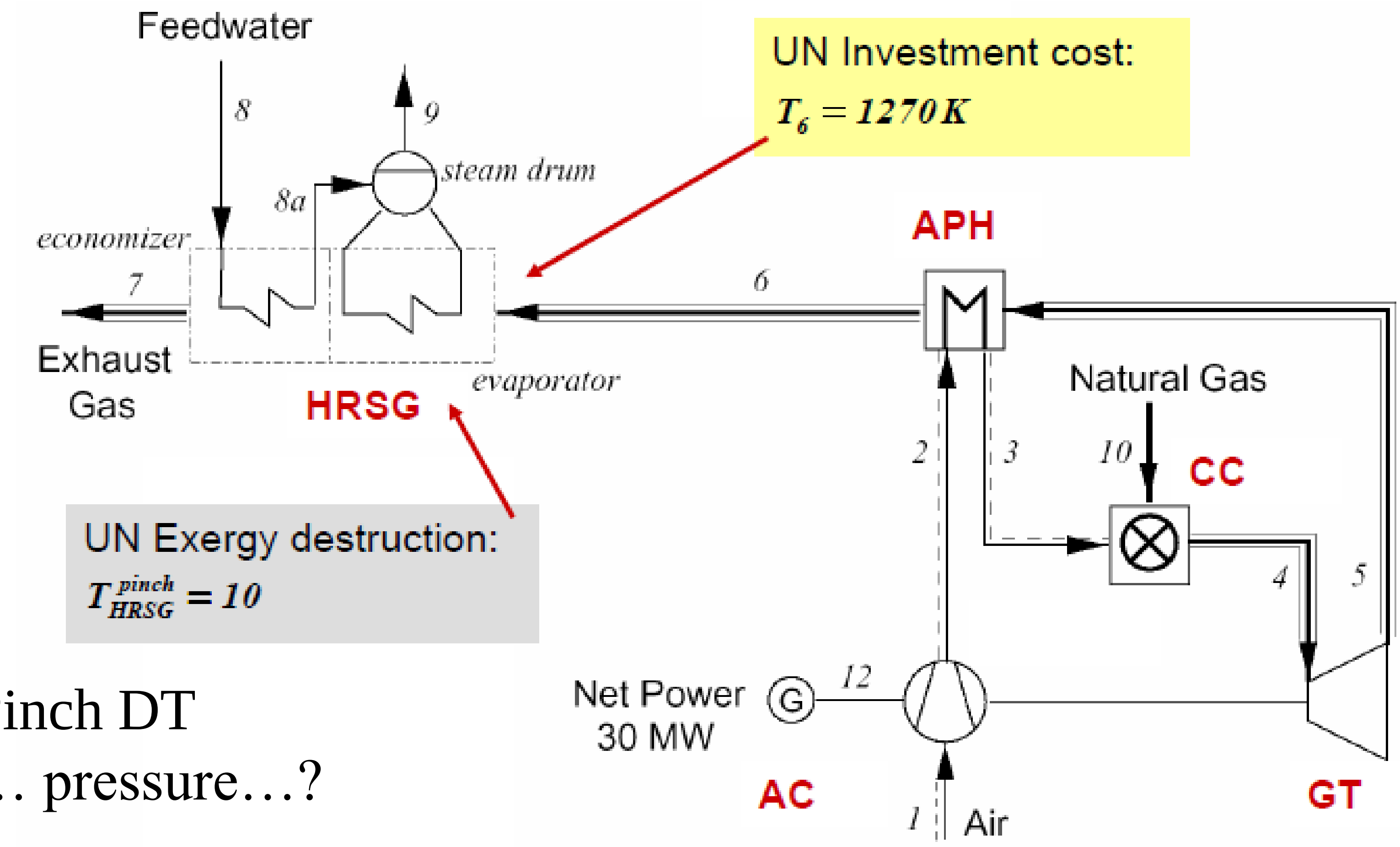
- Isentropic efficiency
- …cooling disregarded…

CGAM – AEA – Unavoidable – ED – IC - AC



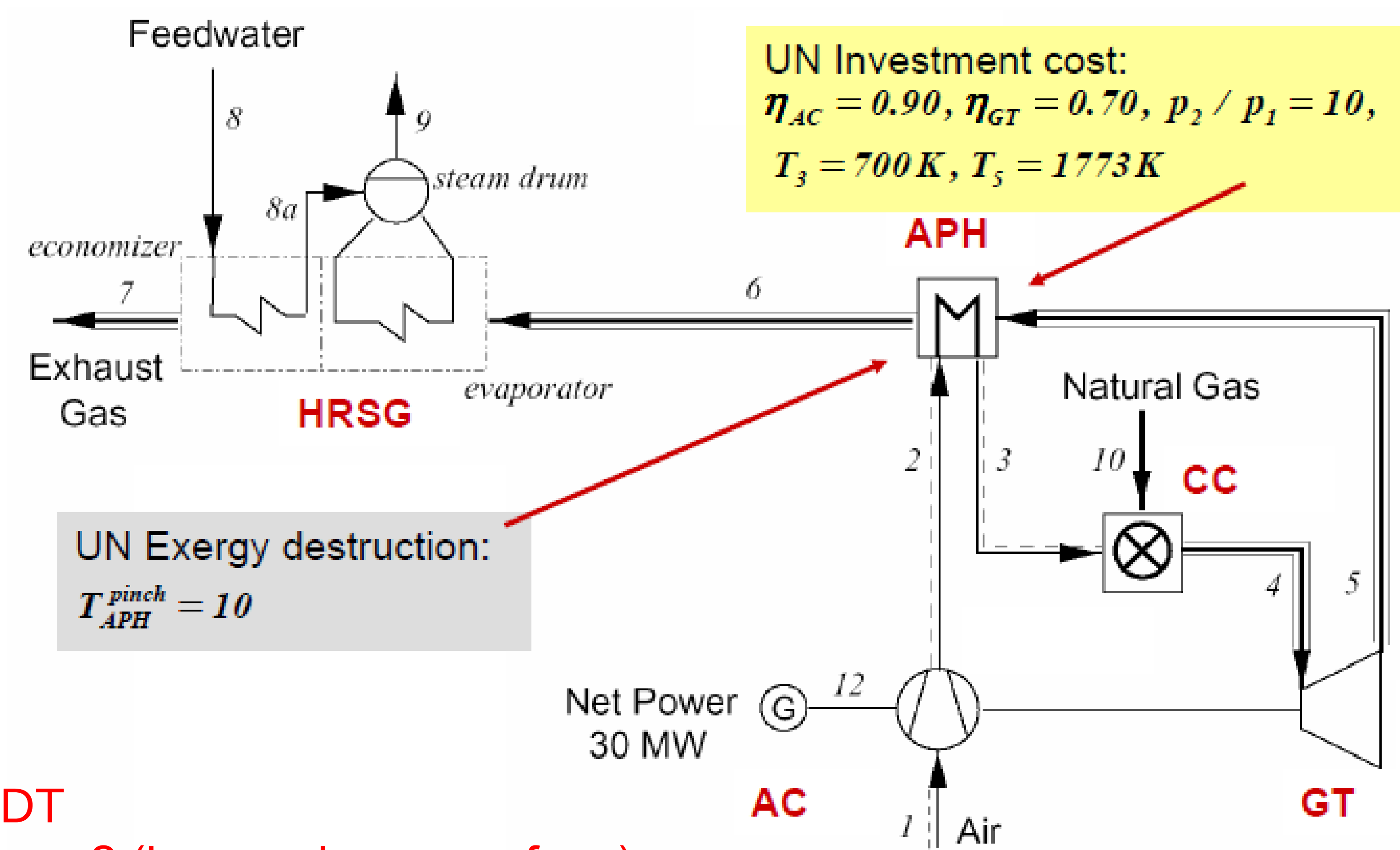
- Isentropic efficiency
- … stall margin…?

CGAM – AEA – Unavoidable – ED – IC - HRSG



- Pinch DT
- … pressure…?

CGAM – AEA – Unavoidable – ED – IC - APH



- Minimum DT
- … pressure…? (lower = larger surface)
- T_5 too high = special materials and difficult design for APH

CGAM – AEA – Unavoidable/Avoidable – Summary

Avoidable AV

Unavoidable UN

Component	$\dot{E}_{P,k}$	$\dot{E}_{D,k}$	$c_{F,k}$	$\dot{Z}_k$	$\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_k^{UN}$	$\dot{E}_{D,k}^{UN}$	$\dot{E}_{D,k}^{AV}$	$\dot{C}_{D,k}^{AV}$	$\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{UN}$	$\dot{Z}_k^{UN}$	$\dot{Z}_k^{AV}$	$\dot{Z}_k^{AV} + \dot{C}_k^{AV}$
	MW	MW	$/GJ	$/h	-	MW	MW	$/h	$/MW	$/h	$/h	$/h
AC	27.54	2.12	18.76	753	0.054	1.49	0.63	43	3.62	100	652	696
APH	14.40	2.63	14.51	189	0.0164	0.24	2.39	125	5.50	79	110	235
CC	59.52	25.84	4.57	68	0.267	15.89	9.95	164	0.126	7	61	225
GT	59.66	3.01	14.51	753	0.027	1.61	1.40	73	1.92	115	638	711
HRSG	12.75	6.23	14.51	264	0.345	4.40	1.83	96	5.46	70	194	290

CGAM – AEA – Unavoidable/Avoidable – Indicators

Cost: Overall, AV, AV% — Capital cost factor f

Component	Overall: $\dot{Z}_k + \dot{C}_{D,k}$ [$/h]	Avoidable: $\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV}$ [$/h]	$\frac{\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV}}{\dot{Z}_k + \dot{C}_{D,k}}$ [%]	Overall: $f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}}$ [%]	Avoidable: $f_k^* = \frac{\dot{Z}_k^{AV}}{\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV}}$ [%]
Air Compressor	869	696	7.7	84	94
Air Preheater	326	235	72.1	58	47
Combustion Chamber	493	225	45.6	14	27
Gas Turbine	910	711	78.1	83	90
HRSG	590	290	49.1	45	67

Capital Cost + Cost of exergy Destruction

Relative incidence of Capital Cost

AEA - Splitting Exergy Destruction: Endogenous, Exogenous, AV, UN

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k}$$

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

endogenous and exogenous

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

unavoidable and avoidable

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

endogenous unavoidable
exogenous unavoidable
endogenous avoidable
exogenous avoidable

AEA - Endogenous, Exogenous

$$\dot{E}_{Fk} = \dot{E}_{Pk} + \left(\dot{E}_{Lk} + \dot{E}_{Dk}\right) \quad \ldots\ldots \text{ Slide 30}\ldots\ldots \quad \dot{E}_{Lk} = 0$$

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \rightarrow \dot{E}^{EN}_{D,k}, \ \dot{E}^{EX}_{D,k}$$

The *endogenous* (*EN*) part of exergy destruction is associated only with the irreversibilities occurring within the *k*-th component when all other components operate in an ideal way and the component being considered operates with its current efficiency.

The *exogenous* (*EX*) part of exergy destruction in the *k*-th component is caused in this component by the irreversibilities that occur in the remaining components.

AEA - Endogenous, Exogenous, AV, UN : Table

$\dot{E}_{D,k}$	*endogenous*	*exogenous*
avoidable	can be reduced through an improvement of the efficiency of the k-th component	can be reduced by a structural optimization of the overall system or by improving the efficiency of the remaining components
unavoidable	cannot be reduced because of technical limitations for the k-th component	cannot be reduced because of technical limitations in other components of the overall system for the given structure

AEA - Splitting Exergoeconomic costs: Endogenous, Exogenous, AV, UN

$$\dot{Z}_k \rightarrow \dot{Z}_k^{AV} + \dot{Z}_k^{UN}$$

$$\dot{Z}_k \rightarrow \dot{Z}_k^{EN} + \dot{Z}_k^{EX}$$

$$\dot{Z}_k^{UN,EN} \rightarrow \dot{Z}_k^{UN,EN} = \dot{E}_{P,k}^{EN} \left(\frac{\dot{Z}_k}{\dot{E}_{P,k}} \right)^{UN}$$

$$\dot{Z}_k^{UN,EX} \rightarrow \dot{Z}_k^{UN,EX} = \dot{Z}_k^{UN} - \dot{Z}_k^{UN,EN}$$

$$\dot{Z}_k^{AV,EN} \rightarrow \dot{Z}_k^{AV,EN} = \dot{Z}_k^{EN} - \dot{Z}_k^{UN,EN}$$

$$\dot{Z}_k^{AV,EX} \rightarrow \dot{Z}_k^{AV,EX} = \dot{Z}_k^{EX} - \dot{Z}_k^{UN,EN}$$

$$\dot{Z}_k = \dot{Z}_k^{UN,EN} + \dot{Z}_k^{UN,EX} + \dot{Z}_k^{AV,EN} + \dot{Z}_k^{AV,EX}$$

Capital Cost

Exergoenvironmental costing

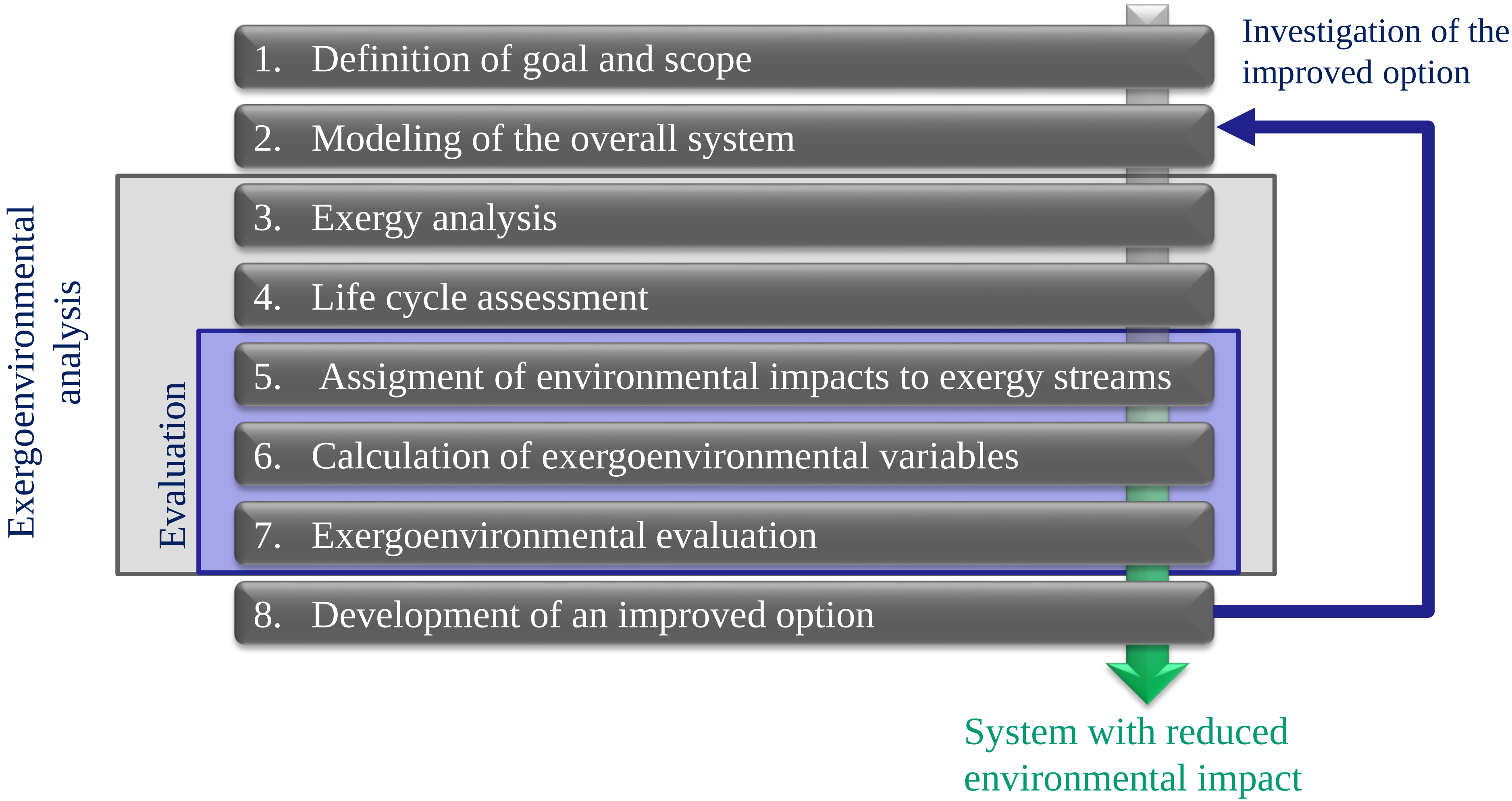
Steps:

1. Exergy analysis

2. LCA
   - → Each relevant system component
   - → All relevant input streams to the overall system

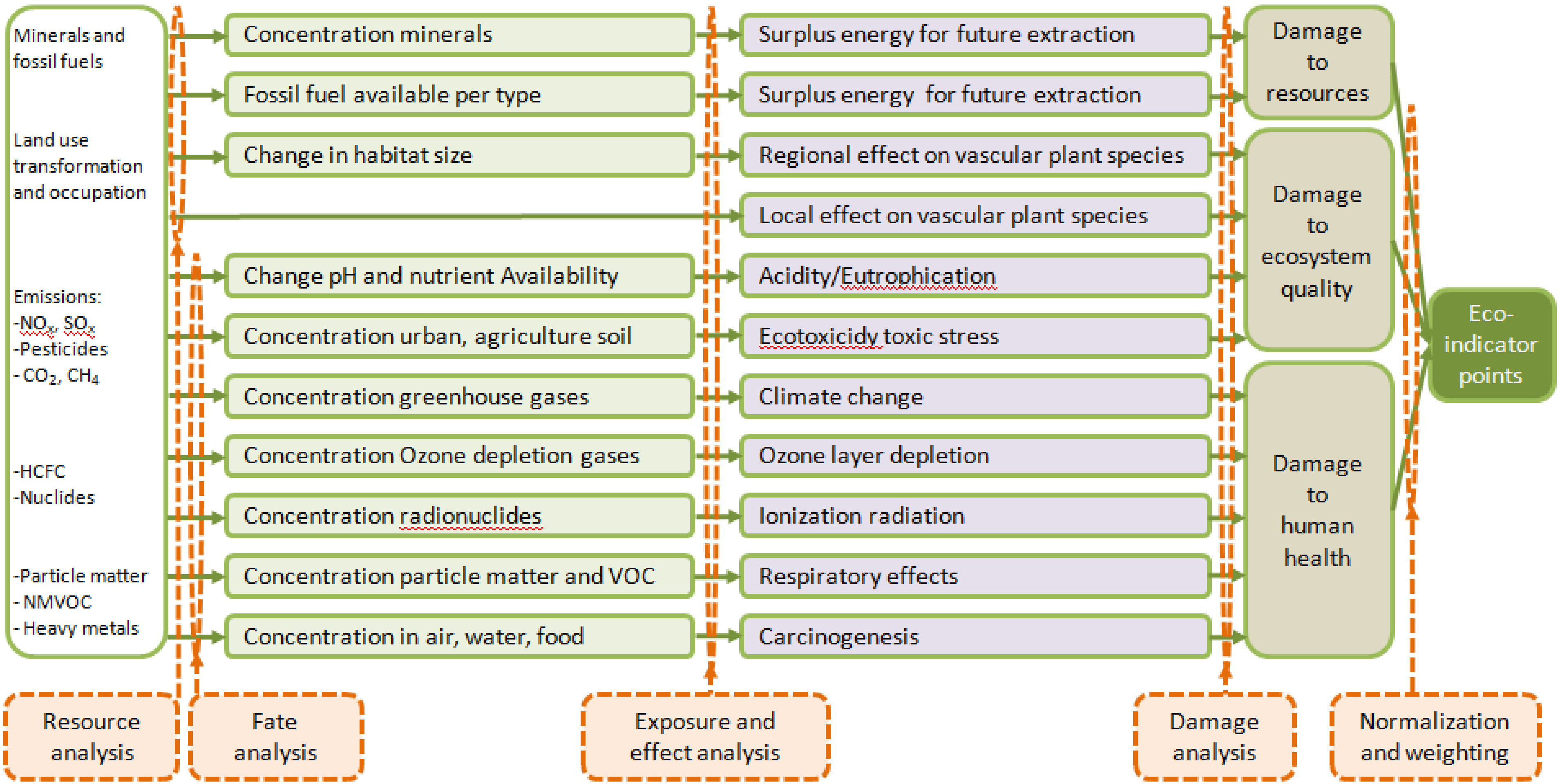
3.
   - → Assigning environmental impacts to exergy systems
   - → Calculation of exergoenvironmental variables
   - → Exergoenvironmental evaluation

Exergo-Environmental Analysis - EEA



Life-Cycle Analysis

General structure and model of the Eco-Indicator 99 LCA method.



ReCiPe Mid-Point (Eco-Indicator 95)

ReCiPe End-Point (Eco-Indicator 99)

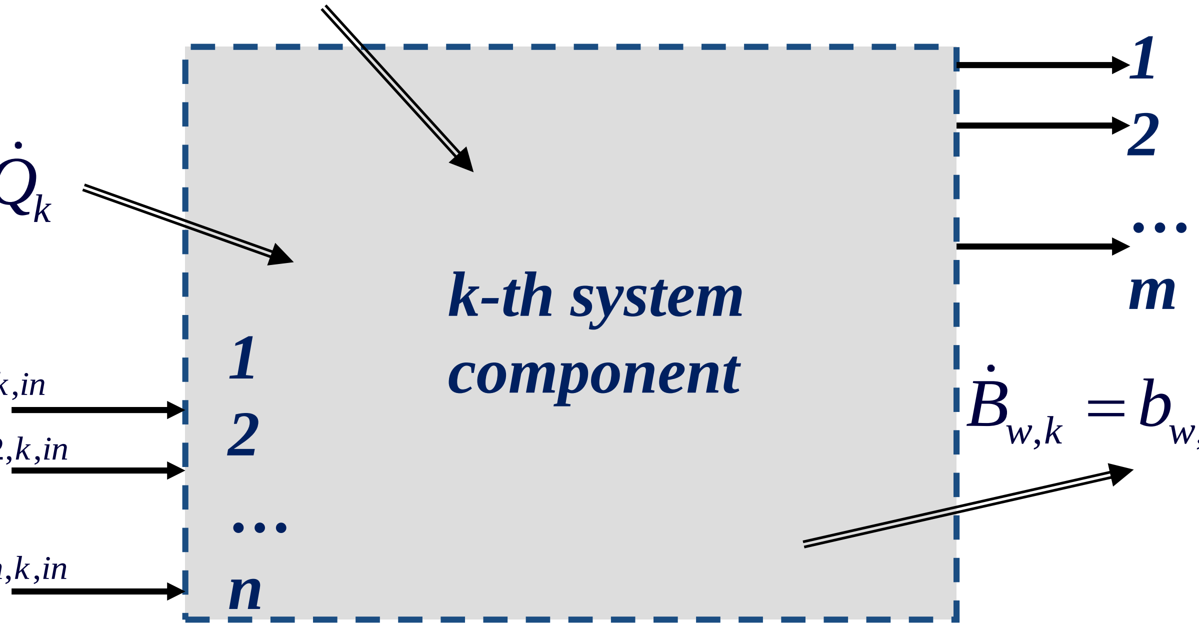
Score

EEA – Transformation Fuel/Products across the component

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI}$$ **Construction, Operation, Decommissioning**

$$\dot{B}_{q,k} = b_{q,k}\,\dot{Q}_k$$

$$\dot{B}_{1,k,out} = b_{1,k,out}\dot{E}_{1,k,out}$$
$$\dot{B}_{2,k,out} = b_{2,k,out}\dot{E}_{2,k,out}$$
$$\dot{B}_{m,k,out} = b_{m,k,out}\dot{E}_{m,k,out}$$



$$\dot{B}_{1,k,in} = b_{1,k,in}\dot{E}_{1,k,in}$$
$$\dot{B}_{2,k,in} = b_{2,k,in}\dot{E}_{2,k,in}$$
$$\dot{B}_{n,k,in} = b_{n,k,in}\dot{E}_{n,k,in}$$

$$\dot{B}_{w,k} = b_{w,k}\dot{W}_k$$

Products

Fuels

Environmental Cost of the kth Component

$$\sum_{i=1}^{n}\dot{B}_{i,k,in} + \dot{B}_{q,k} + \dot{Y}_k = \sum_{i=1}^{m}\dot{B}_{i,k,out} + \dot{B}_{w,k}$$

EEA – Env. Impact of Exergy Destruction; Performance Indicators.

Environmental impact of stream j

$$\dot{B}_j = b_j \dot{E}_j$$

$$\dot{B}_j \left(Pts / s \right)$$
$$b_j \left(Pts / GJ\ exergy \right)$$

Environmental Impact balances

$$\dot{B}_{P,k} = \dot{B}_{F,k} + \dot{Y}_k$$

$$b_{P,k} \dot{E}_{P,k} = b_{F,k} \dot{E}_{F,k} + \dot{Y}_k$$

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

Auxiliary environmental impact equations
(Meyer et al, 2008)

Environmental impact of exergy destruction

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

$$\dot{B}_{TOT,k} = \dot{Y}_k + \dot{B}_{D,k}$$

Relative difference

$$r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}}$$

Exergoenvironmental factor

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

EEA – Evaluation of Results

Steps:

1. Identify the environmentally relevant system components: $\uparrow \dot{B}_{TOT,k}$

2. Select the ones that have the highest improvement potential: $\uparrow r_{b,k}$

3. $f_{b,k}$

   - $\uparrow f_{b,k} \Rightarrow \uparrow \dot{Y}_k$ → The component related impact dominates the overall impact
   - $\downarrow f_{b,k} \Rightarrow \uparrow \dot{B}_{D,k}$ → The thermodynamic inefficiencies are the dominant source of environmental impact

Advanced Exergo-Environmental Analysis AEEA

Advanced exergy analysis → $\dot{E}_{D,k}$

- $\dot{E}^{AV}_{D,k}$ / $\dot{E}^{UN}_{D,k}$
- $\dot{E}^{EN}_{D,k}$ / $\dot{E}^{EX}_{D,k}$

Ad. exergoeconomic analysis → $\dot{Z}_{k}$

- $\dot{Z}^{AV}_{D,k}$ / $\dot{Z}^{UN}_{D,k}$
- $\dot{Z}^{EN}_{D,k}$ / $\dot{Z}^{EX}_{D,k}$

Advanced exergoenvironmental analysis → $\dot{Y}_{k}$

- $\dot{Y}^{AV}_{D,k}$ / $\dot{Y}^{UN}_{D,k}$
- $\dot{Y}^{EN}_{D,k}$ / $\dot{Y}^{EX}_{D,k}$

Avoidable/Unavoidable $\dot{Y}_k$

$\dot{Y}_k^{UN}$ → $\dot{Y}_{k,\min}$ min environmental impact

$$\dot{Y}_k^{AV} = \dot{Y}_k - \dot{Y}_k^{UN}$$

$$\dot{Y}_k = \dot{Y}_k^{AV} + \dot{Y}_k^{UN}$$

$$\left(\frac{\dot{Y}_k}{\dot{E}_{P,k}}\right)^{UN} \rightarrow \dot{Y}_k^{UN} = \dot{E}_{P,k}^{real}\left(\frac{\dot{Y}_k}{\dot{E}_{P,k}}\right)^{UN}$$

The *unavoidable* component-related environmental impact is calculated using the minimal environmental impact from each category, combining materials and manufacturing methods.

AEA- AEEA - Endogenous/Exogenous

$$\dot{E}^{EN}_{D,k} \rightarrow \dot{E}_{D,k} \text{ when } \varepsilon_k = \varepsilon_{real} \text{ and } \varepsilon_{j\neq k} = 1$$

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

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

$$\dot{Z}_k = \dot{Z}^{EN}_k + \dot{Z}^{EX}_k$$

$$\dot{Z}^{EN}_k = \dot{E}^{EN}_{P,k} \left(\frac{\dot{Z}_k}{\dot{E}_{P,k}} \right)^{real}$$

$$\dot{Y}_k = \dot{Y}^{EN}_k + \dot{Y}^{EX}_k$$

$$\dot{Y}^{EN}_k = \dot{E}^{EN}_{P,k} \left(\frac{\dot{Y}_k}{\dot{E}_{P,k}} \right)^{real}$$

AEEA - Splitting Exergoenvironmental issues: Endogenous, Exogenous, AV, UN

$$\dot{Y}_k \rightarrow \dot{Y}_k^{AV} + \dot{Y}_k^{UN}$$

$$\dot{Y}_k \rightarrow \dot{Y}_k^{EN} + \dot{Y}_k^{EX}$$

$$\dot{Y}_k^{UN,EN} \rightarrow \dot{Y}_k^{UN,EN} = \dot{E}_{P,k}^{EN} \left(\frac{\dot{Y}_k}{\dot{E}_{P,k}} \right)^{UN}$$

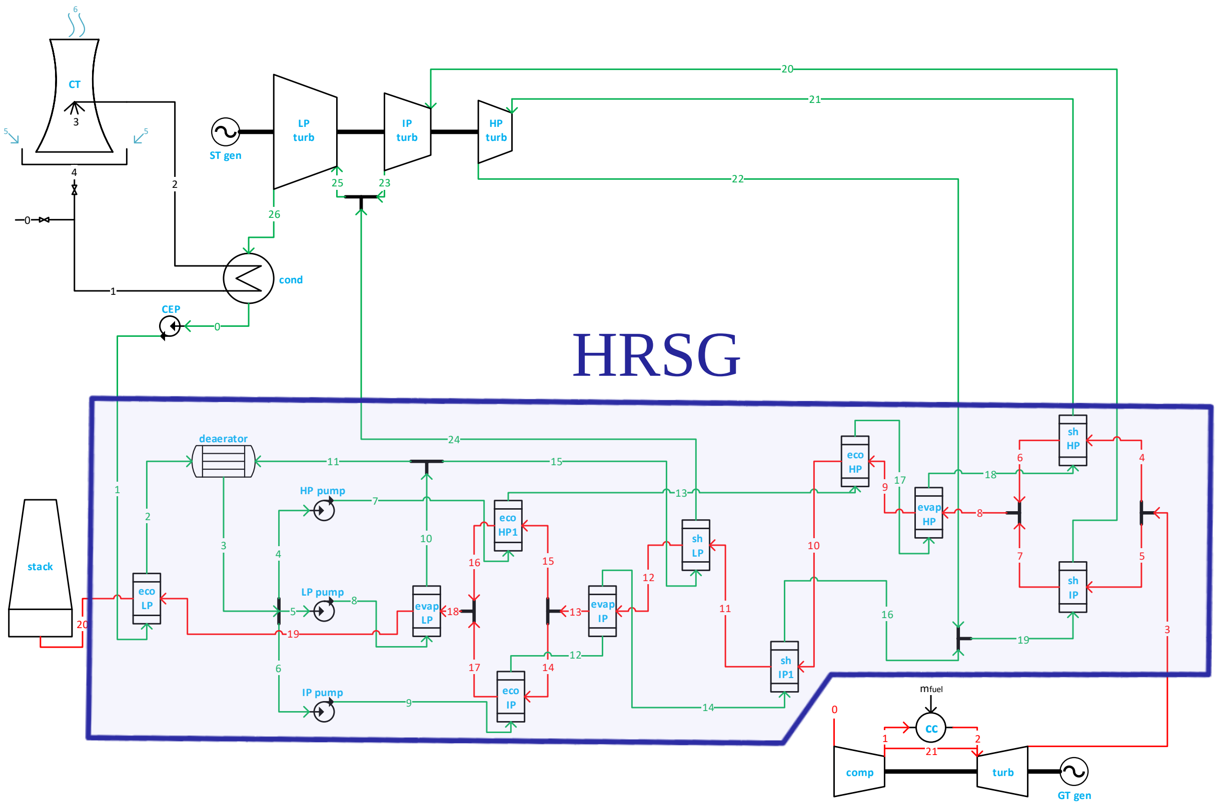
$$\dot{Y}_k^{UN,EX} \rightarrow \dot{Y}_k^{UN,EX} = \dot{Y}_k^{UN} - \dot{Y}_k^{UN,EN}$$

$$\dot{Y}_k^{AV,EN} \rightarrow \dot{Y}_k^{AV,EN} = \dot{Y}_k^{EN} - \dot{Y}_k^{UN,EN}$$

$$\dot{Y}_k^{AV,EX} \rightarrow \dot{Y}_k^{AV,EX} = \dot{Y}_k^{EX} - \dot{Y}_k^{UN,EN}$$

$$\dot{Y}_k = \dot{Y}_k^{UN,EN} + \dot{Y}_k^{UN,EX} + \dot{Y}_k^{AV,EN} + \dot{Y}_k^{AV,EX}$$

CCGT → IS CCGT (Integrated Solar) Power Plant



Original Combined Cycle Gas Turbine (CCGT) Power Plant

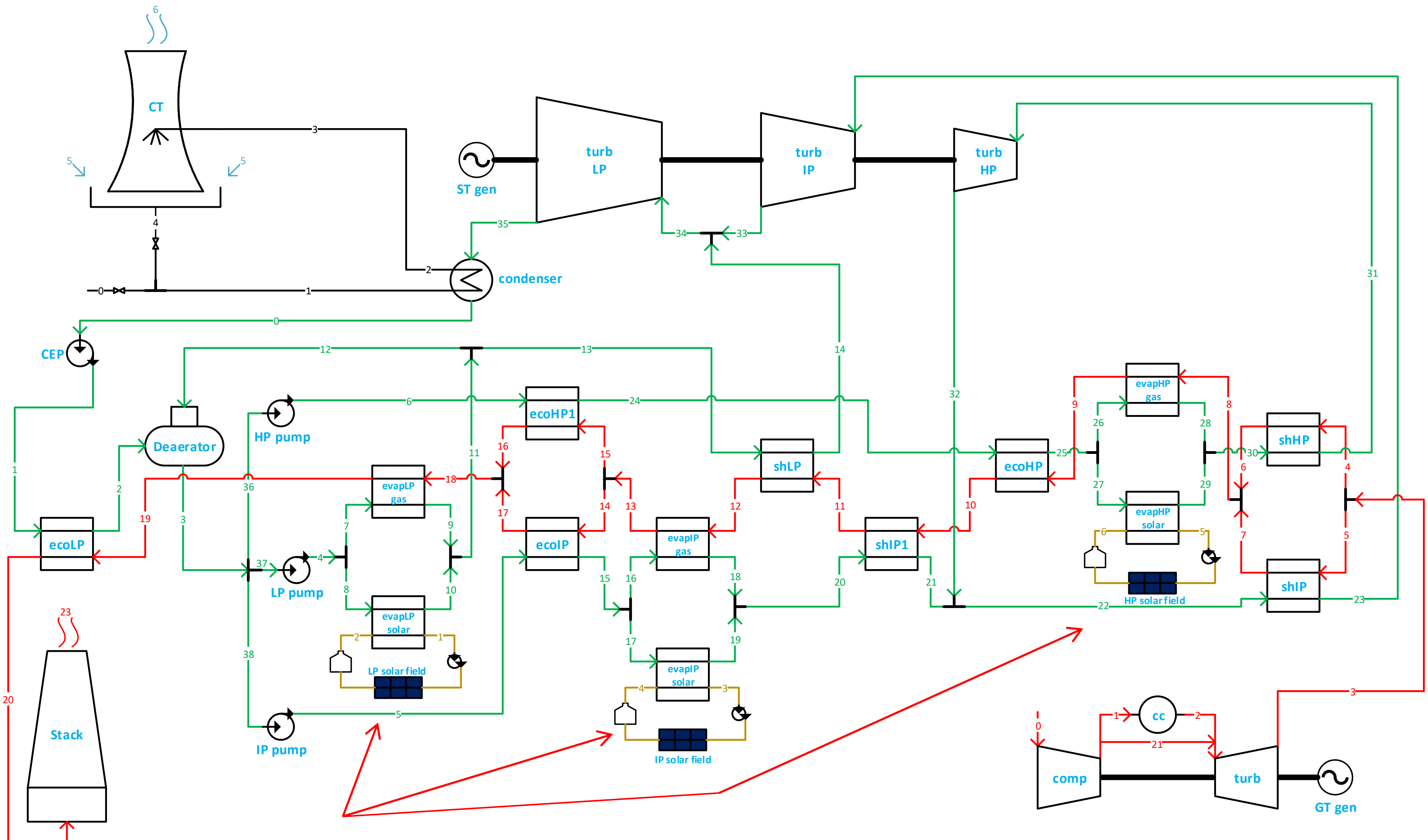
Stalowa Wola, Poland

Main parameters at design conditions					
Configuration	Air/Steam mass flow	W_{GT}	W_{ST}	Electrical efficiency	Exergetic efficiency
CCGT	639/110 kg/s	288,81 MWe	153,97 MWe	57,91 %	**55,70 %**
ISCCGT	639/153 kg/s	288,81 MWe	194,01 MWe	63,45 %	**47,85 %**

Power Boosting

Natural Gas only (marginal efficiency)

IS-CCGT Power Plant



Smart Integrated Solar CCGT

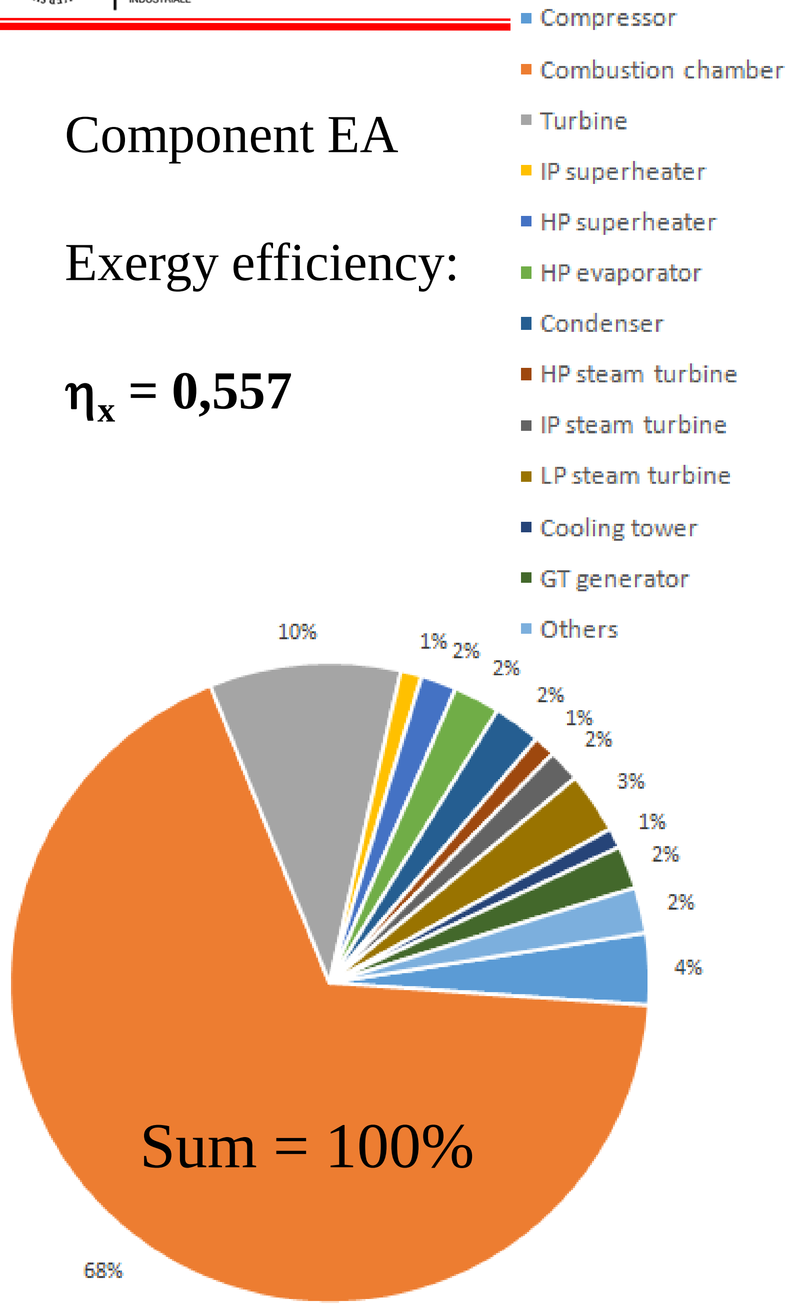
Purpose: promote heat recovery from CCGT exhaust gas stream

CCGT Power Plant

Component EA

Exergy efficiency:

$\eta_x = 0{,}557$

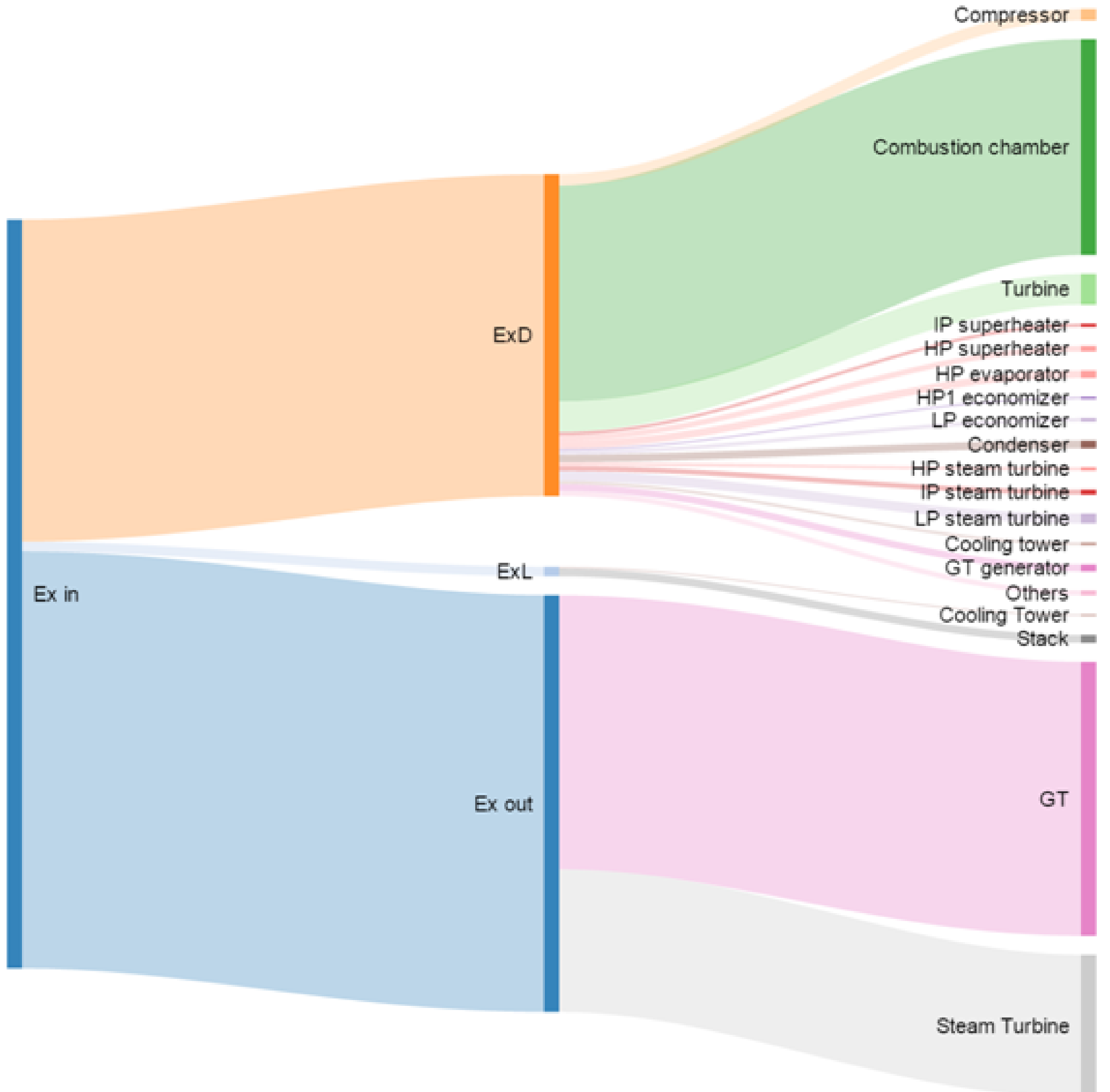


Component name	$\dot{E}_F$ [kW]	$\dot{E}_P$ [kW]	y_D [%]	ε_k [%]
Compressor	265994	253872	1,5370779	95,44
Combustion chamber	788641	561295	28,8274768	71,17
Turbine	594534	562150	4,106375	94,55
IP superheater	31974	28421	0,4505541	88,89
HP superheater	47179	41163	0,7628026	87,25
HP evaporator	64779	56877	1,0020155	87,8
HP economizer	23276	22408	0,1101203	96,27
IP1 superheater	323	289	0,0042624	89,58
LP superheater	1032	838	0,0245586	81,22
IP evaporator	8881	8421	0,0584069	94,81
IP economizer	1471	1047	0,0536912	71,21
HP1 economizer	15855	13602	0,2856538	85,79
LP evaporator	7365	6353	0,1284129	86,25
IP pump	32,70	29,10	0,0004573	88,97
LP pump	1,648	1,466	0,0000231	88,97
HP pump	1388,924	1236	0,0193698	89
Deaerator	802	648	0,0195797	80,76
LP economizer	10168	6176	0,5061378	60,74
Main pump	25,90	22,22	0,0004666	85,79
Condenser	13211	5181	1,0182034	39,22
HP steam turbine	36278	32597	0,4667696	89,85
IP steam turbine	58763	53251	0,6988933	90,62
LP steam turbine	78477	68125	1,3126646	86,81
Cooling tower	10419	7062	0,4255859	67,79
GT generator	296155	288881	0,922368	97,54

CCGT Power Plant

Component EA

Grassmann Diagram



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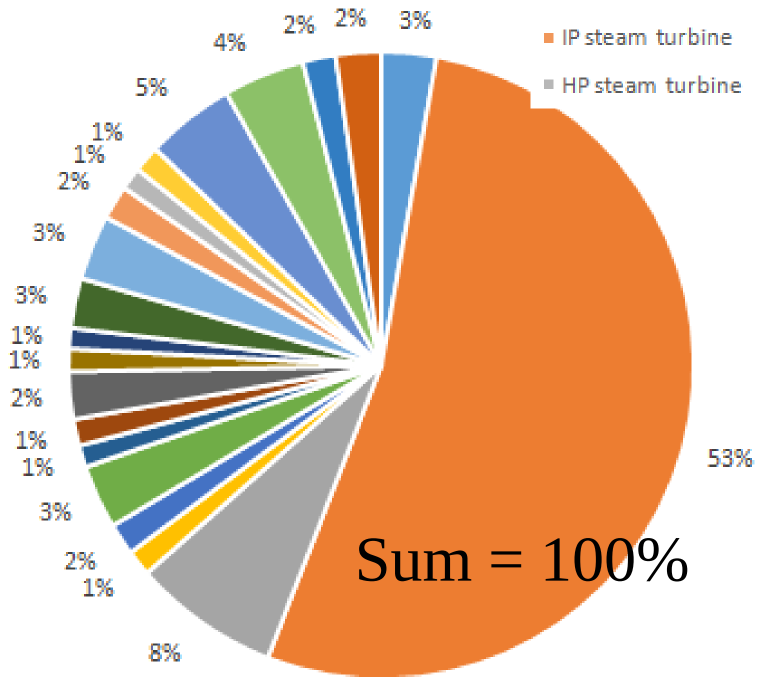
IS-CCGT Power Plant

Component EA

Exergy efficiency:

$\eta_x = 0{,}478$



Component name	$\dot{E}_F$ [kW]	$\dot{E}_P$ [kW]	y_D [%]	ε_k [%]
Compressor	265994,2	253872,2	4,557	95,44
Combustion chamber	788640,6	561295,2	28,83	71,17
Gas Turbine	594534,2	562149,6	5,447	94,55
IP superheater	41667,6	35901,85	13,84	86,16
HP superheater	51992,34	44976,22	13,49	86,51
Evap HP-solar	50140,62	36049,38	28,1	71,9
Evap HP-gas	50663,9	45777,32	9,645	90,35
HP economizer	29589,14	27108,18	8,385	91,62
IP1 superheater	188,643	179,026	5,098	94,9
LP superheater	1673,792	1367,374	18,31	81,69
IP Evaporator-gas	3137,687	3007,638	4,145	95,86
IP Evaporator -solar	14424,07	8591,062	40,44	59,56
IP economizer	1853,804	1546,838	16,56	83,44
HP1 economizer	17117,72	14539,18	15,06	84,94
LP evap-gas	4438,862	3945,844	11,11	88,89
LP evap-solar	22397,26	11889,45	46,92	53,08
HP pump	1842,051	1638,85	11,03	88,97
LP pump	4,095	3,642	11,06	88,94
IP pump	45,3	40,29	11,06	88,94
Deaerator	4019,027	3301,109	17,86	82,14
LP economizer	10998,27	6014,47	45,31	54,69
CEP	36,121	30,989	14,21	85,79
Cooling tower	14302,75	9695,137	32,21	67,79
Condenser	18135,53	7111,938	60,78	39,22
LP steam turbine	105373,9	90979,27	13,66	86,34

IS-CCGT Power Plant

Component name	$\dot{E}_F$ [kW]	$\dot{E}_P$ [kW]	y_D [%]	ε_k [%]
IP steam turbine	74126,13	66582,77	10,18	89,82
HP steam turbine	44254,14	39245,81	11,32	88,68
IP solar collectors	20329,44	14424,07	29,05	70,95
HP solar collectors	69820,4	50140,62	28,19	71,81
LP solar collectors	40405,23	22397,26	44,57	55,43
GT generator	296155,4	288881,2	2,456	98,6
ST generator	196807,9	194052,5	1,4	98,6

Component EA (follows)

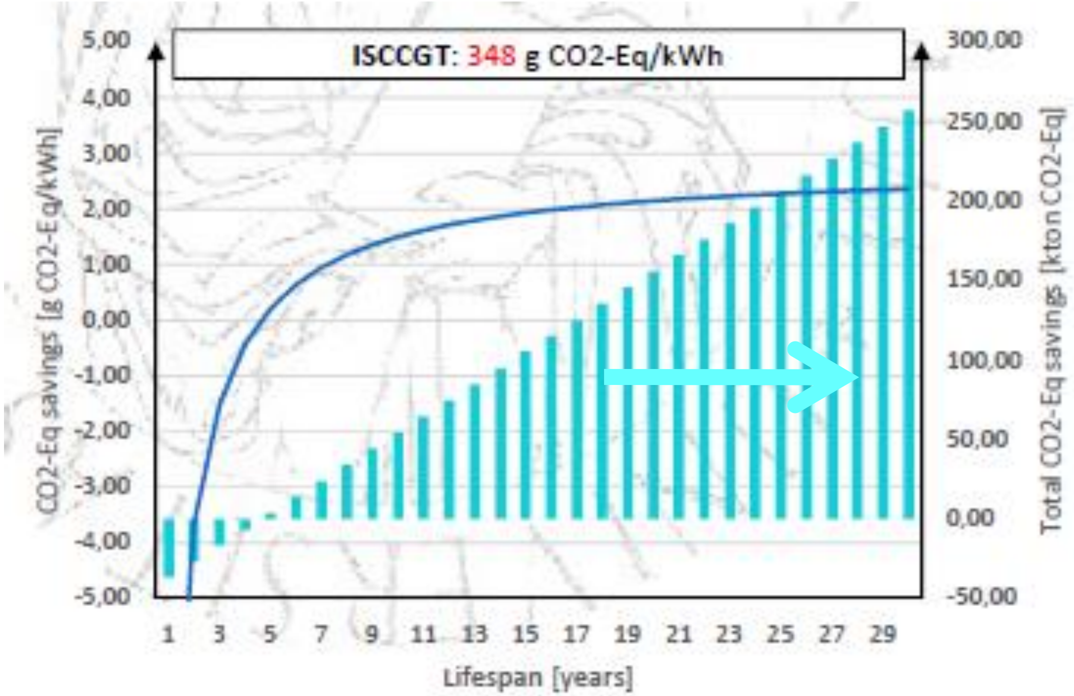
Exergy efficiency:

η_x **= 0,478**

Carbon Footprint pay-off

Solar Hybridization of a CCGT

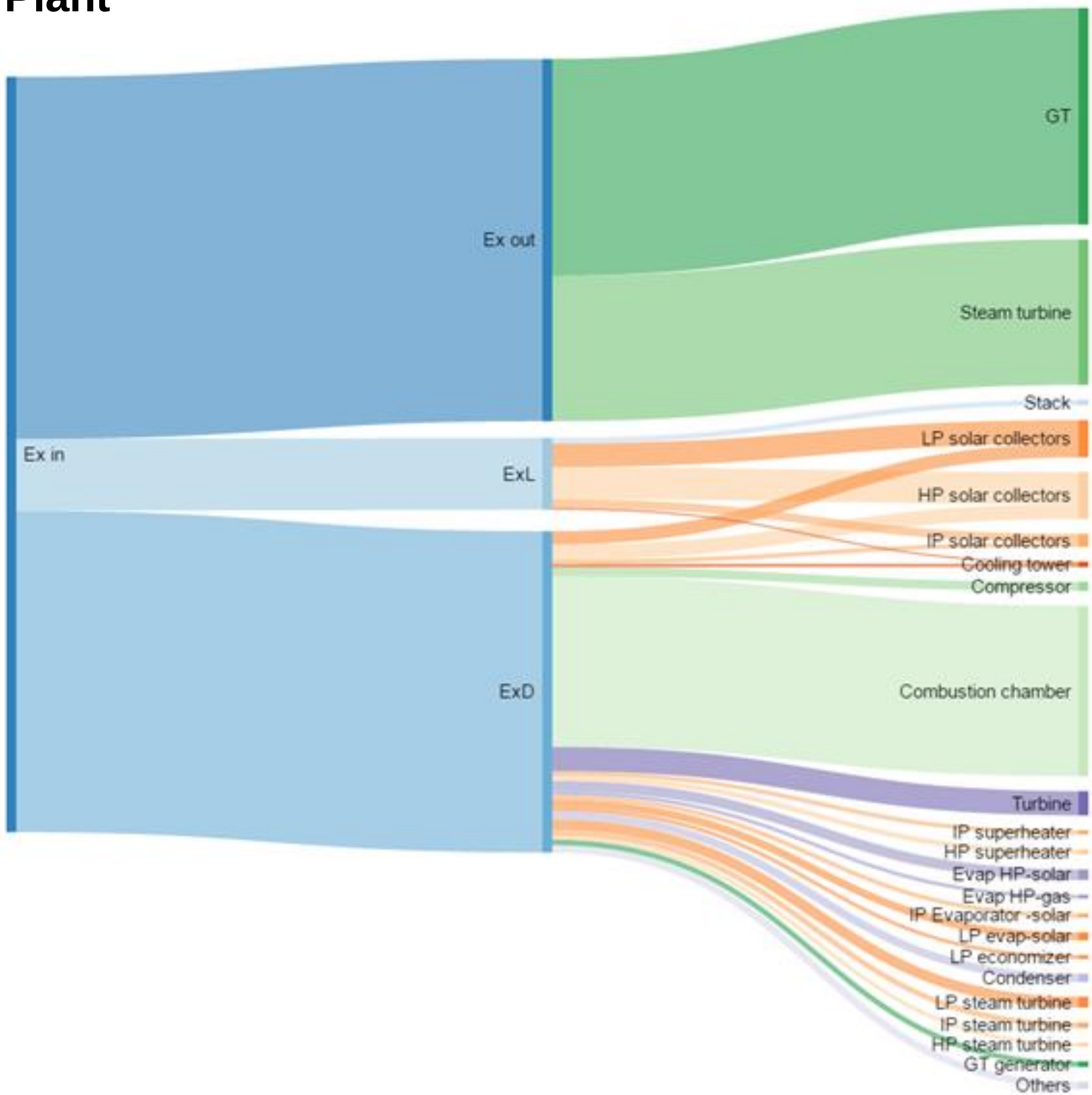
20 yrs = 200000 T_{CO2} avoided



IS-CCGT Power Plant

Component EA

Grassmann Diagram



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CCGT – ISCCGT Power Plant – Capital Costs (PEC)

Component name	CCGT power plant [$]	ISCCGT power plant [$]
Compressor	29504545	29504545
Combustion chamber	4410060	4410060
Gas turbine	17395535	17395535
HRSG	12857944	17189792
HP steam turbine	6097193	6735891
IP steam turbine	5462819	9871138
LP steam turbine	9554210	11975344
LP water pump	2346	4478
IP water pump	19579	24676
HP water pump	280401	342623
CEP	16592	21011
Cooling tower	9728613	13355529
Condenser	4445186	6102746
GT generator	4620851	4620851
ST generator	3118879	3596056
LP solar thermal collectors	0	21555016
IP solar thermal collectors	0	13135590
HP solar thermal collectors	0	47490210

CCGT – ISCCGT Power Plant – Capital Costs (PEC) - HRSG

	Conventional combined cycle		Integrated solar combined cycle	
Component name	HT surface [m²]	Capital cost [$]	HT surface [m²]	Capital cost [$]
LP eco	16899	1212479	16899	1351598
LP eva-solar	0	0	14460	1291292
LP eva-gas	36329	689723	21690	428566
LP sh	3911	70014	3911	120293
IP eco	7294	116285	7294	150813
IP eva-solar	0	0	6368	649689
IP eva-gas	15894	623416	9553	227450
IP1 sh	1378	21979	1378	13330
IP sh	10233	1547179	10233	2038391
HP1 eco	20504	1253798	20504	1479624
HP eco	24823	1479466	24823	1918673
HP eva-solar	0	0	11807	2231357
HP eva-gas	29518	3560841	17710	2833491
HP sh	12524	2282949	12524	2543498

Decrease

Increase

CCGT – ISCCGT Power Plant – Direct Costs - Assumptions

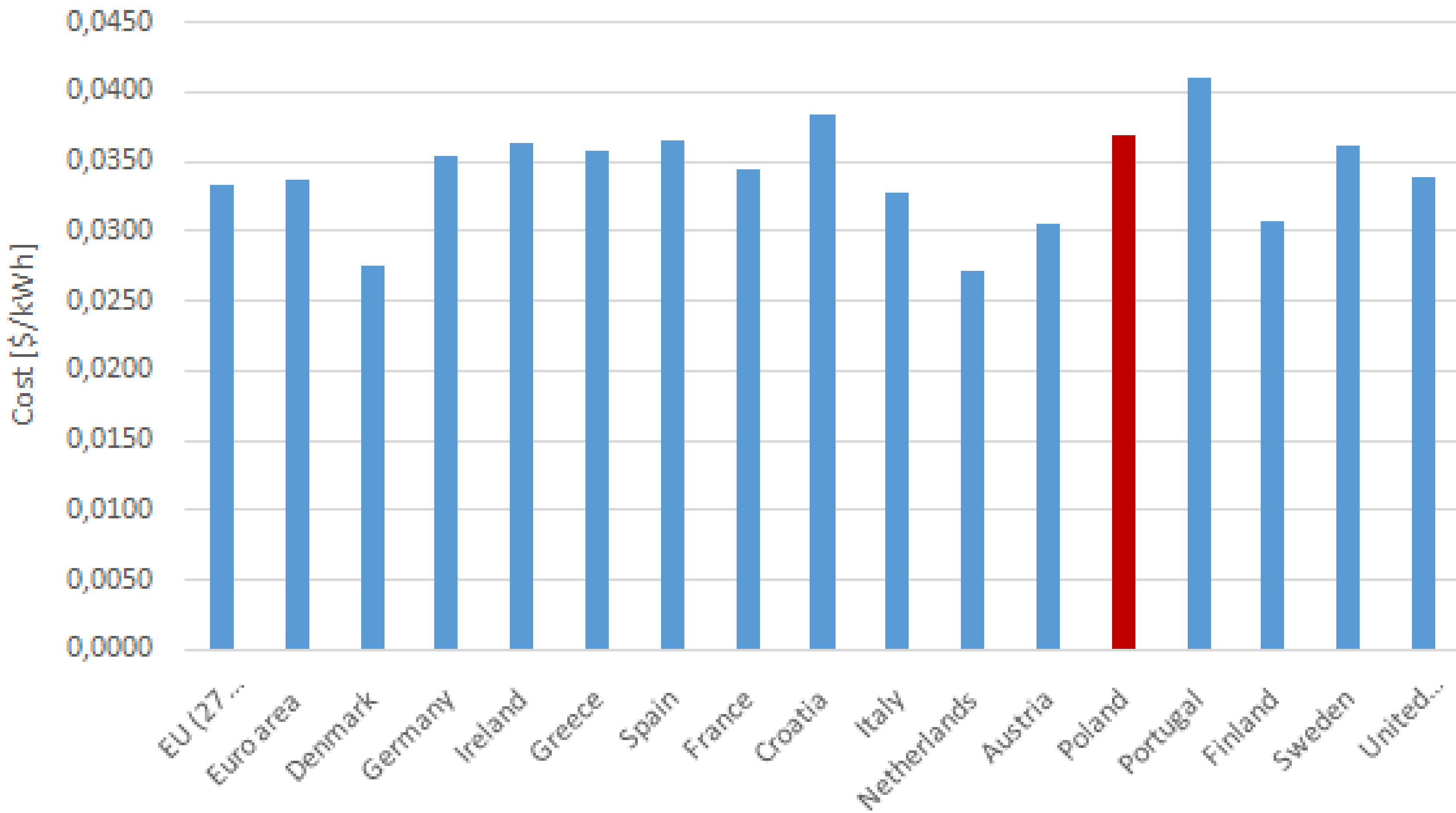
- Installation 20 – 90 % of PEC
- Piping 10 – 70 % of PEC
- Instruments and control systems 6 – 40 % of PEC
- Land occupation 10 – 15 % of PEC
- Civil works 10 – 80 % of PEC
- Service facilities 30 – 100 % of PEC
- Design 25-75 % of PEC
- Construction 15 % of DC
- Start-up 5 – 12 % of PEC

CCGT – ISCCGT Power Plant – Direct and Indirect Costs - Results

Component name	DC and IC for the CCGT plant [$]	DC and IC for the ISCC plant [$]
Compressor	94119498	94119498
Combustion chamber	14068091	14068091
Turbine	55491755	55491755
Heat Recovery Steam Generator	41016840	54835436
Steam turbine	76924374	91177769
Low pressure pump	7487	14287
Intermediate pressure pump	62457	78719
High pressure pump	894480	1092969
CEP	52929	67028
Cooling tower	31034277	42604140
Condenser	14180146	19467762
GT generator	14740514	14740514
ST generator	9949224	11471418
LP solar field	0	68760501
IP solar field	0	41902532
HP solar field	0	151493770

Increase of steam flow rate

CCGT – ISCCGT Power Plant – Fuel Cost (Natural Gas)



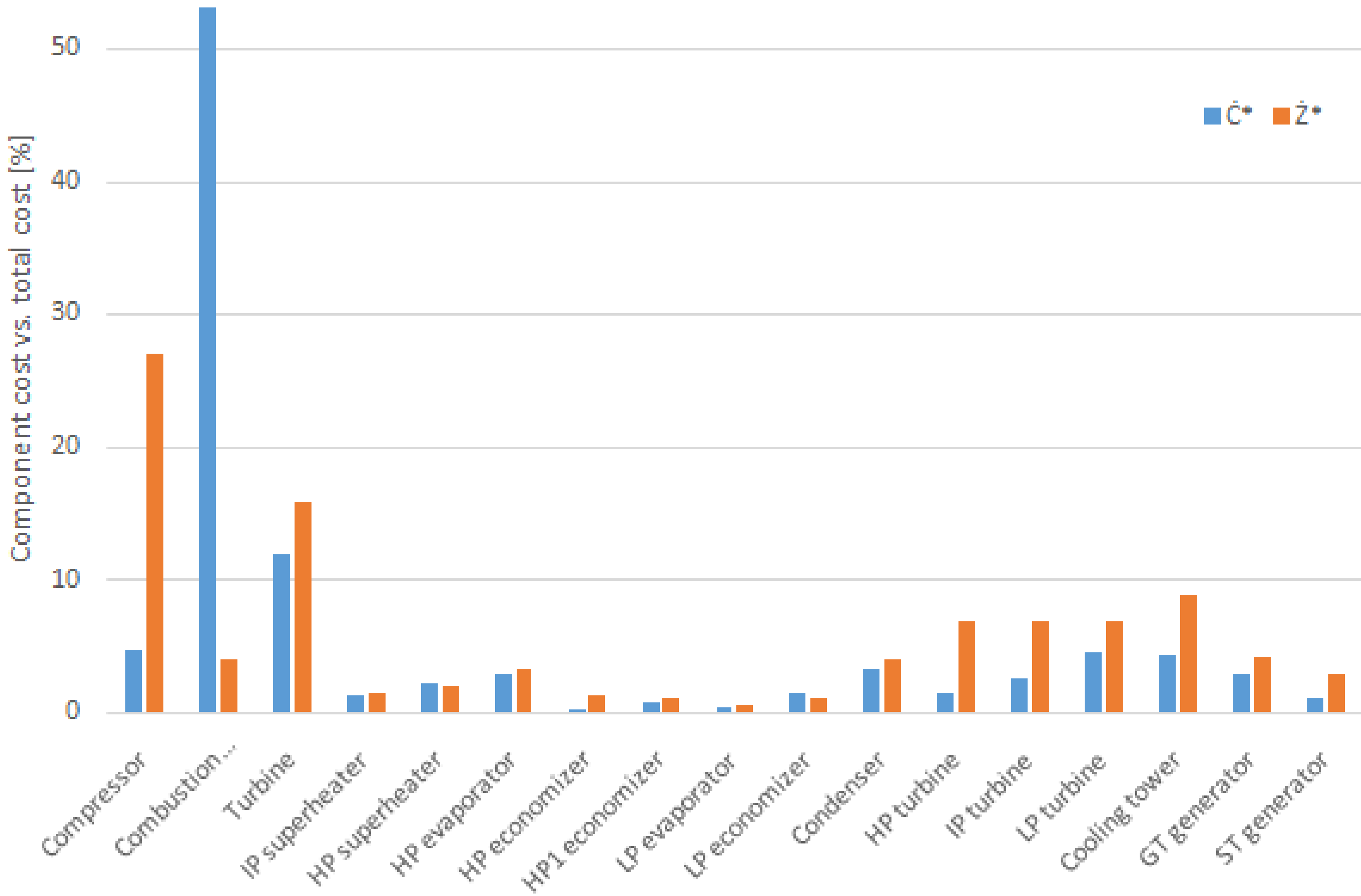
CCGT Power Plant

EEA

Exergo-Economic Analysis

Component name	$\dot{C}_D$ [\$·h^{-1}]	$\dot{Z}_{TOT}$ [\$·h^{-1}]	$\dot{C}_{TOT}$ [\$·h^{-1}]	r_c [%]	f_c [%]
Compressor	732,6	1236,24	1968,84	12,83	62,79
Combustion chamber	8096,4	184,7815	8280	41,43	2,232
Turbine	1810,8	728,8729	2539,44	8,08	28,7
IP superheater	198,684	64,82678	263,52	16,58	24,6
HP superheater	336,348	95,65555	432	18,77	22,14
HP evaporator	441,72	149,1992	591,12	18,59	25,24
HP economizer	48,564	61,98959	110,556	8,823	56,07
IP1 superheater	1,87956	0,91328	2,79288	17,29	32,7
LP superheater	10,8288	2,93358	13,7628	29,38	21,32
IP evaporator	25,7544	26,1211	51,876	11,02	50,35
IP economizer	23,6772	4,87235	28,548	48,76	17,07
HP1 economizer	125,964	52,5341	178,488	23,47	29,43
LP evaporator	56,628	28,89938	85,536	24,08	33,79
IP pump	0,30366	0,82036	1,12392	45,88	72,99
LP pump	0,015311	0,09833	0,113652	92,05	86,53
HP pump	12,8628	11,74881	24,6096	23,64	47,74
Deaerator	10,7172	1,7545	12,4704	27,73	14,07
LP economizer	223,2	50,80287	273,996	79,34	18,54
Feedwater pump	0,309852	0,88039	1,19016	63,61	73,97
Stack	0	3,61267	3,6144	0,7756	100
Condenser	514,44	186,2533	700,56	211,1	26,58
HP turbine	239,58	317,3865	556,92	26,25	56,98
IP turbine	380,52	317,3865	698,04	18,98	45,47
LP turbine	696,6	317,3865	1014,12	22,12	31,3
Cooling tower	668,88	407,6289	1076,4	76,49	37,87
GT generator	439,56	193,6137	633,24	3,627	30,58

CCGT Power Plant – Component Cost of Exergy Destruction and Capital Cost rate



IS CCGT Power Plant

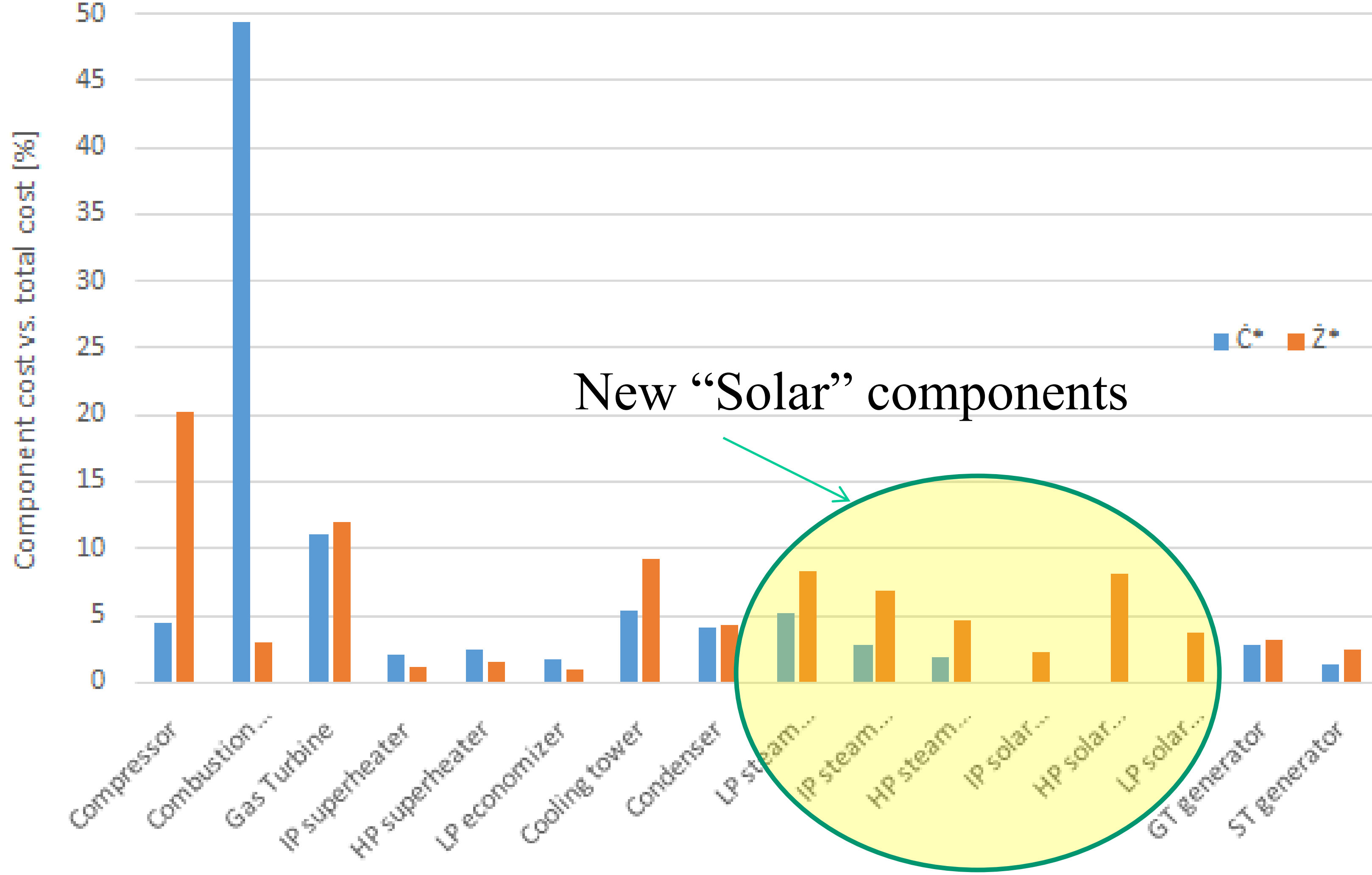
EEA

Exergo-Economic Analysis

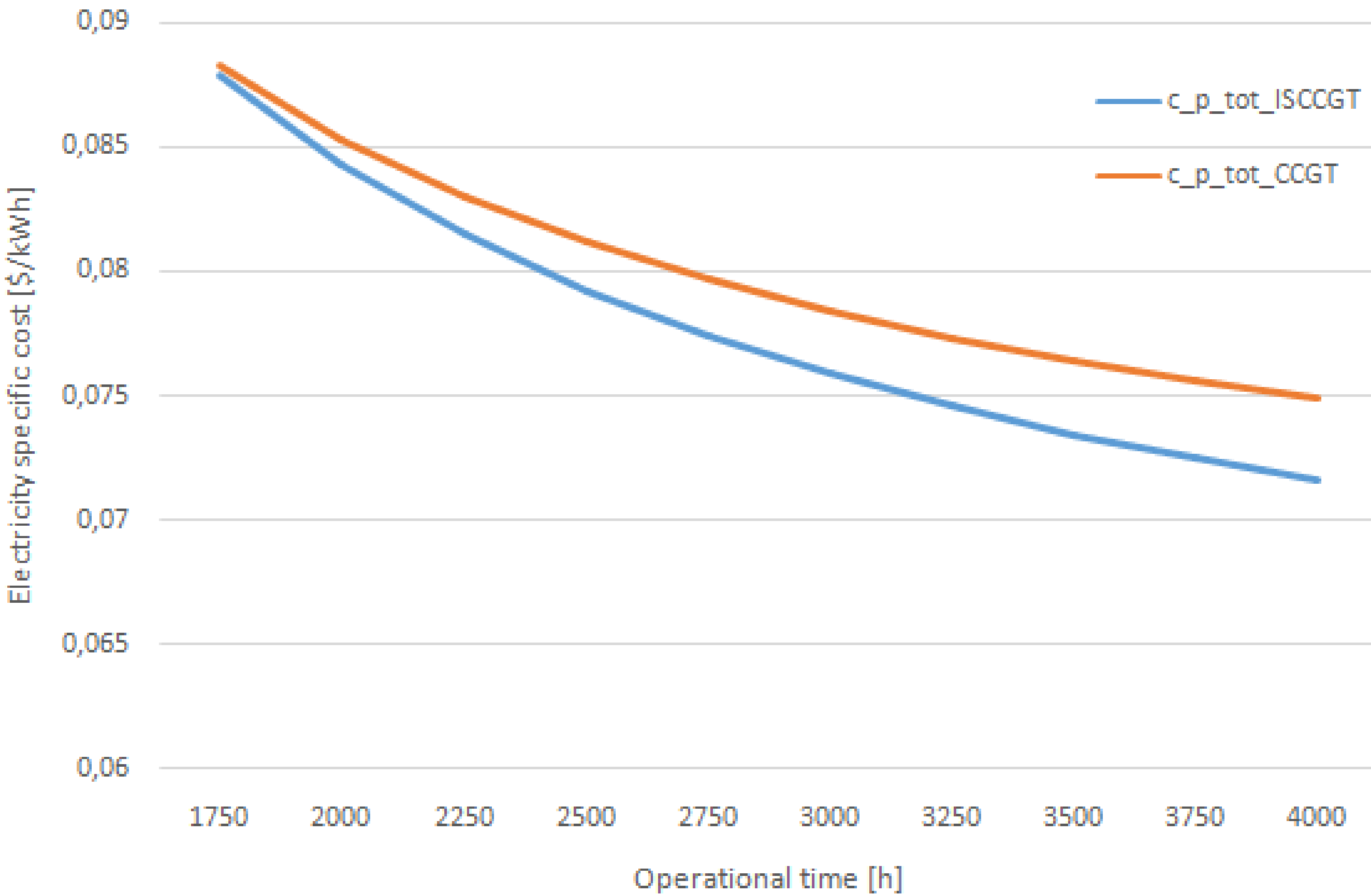
Since the specific fuel cost is zero, the exergy destruction cost rate is also zero →

Component name	$\dot{C}_D$ [$\$\cdot h^{-1}$]	$\dot{Z}_{TOT}$ [$\$\cdot h^{-1}$]	$\dot{C}_{TOT}$ [$\$\cdot h^{-1}$]	r_c [%]	f_c [%]
Compressor	732,6	1236,24	1968,84	12,83	62,79
Combustion chamber	8096,4	184,788	8280	41,43	2,232
Gas Turbine	1810,8	729	2539,44	8,08	28,7
IP superheater	322,38	64,836	387,36	19,29	16,74
HP superheater	392,4	95,652	487,8	50,52	19,6
Evap HP-solar	138,42	93,492	231,912	65,49	40,32
Evap HP-gas	273,24	118,728	392,04	15,31	30,29
HP economizer	138,708	80,388	219,096	14,46	36,69
IP1 superheater	0,53784	0,55836	1,0962	10,95	50,95
LP superheater	17,1324	26,1216	43,272	56,57	60,39
IP Evaporator-gas	7,272	9,5292	16,8012	9,991	56,72
IP Evaporator -solar	55,08	27,2232	82,296	101,4	33,07
IP economizer	17,1648	6,318	23,4828	130,4	26,91
HP1 economizer	144,18	61,992	206,172	25,36	30,07
LP evap-gas	27,5652	17,9568	45,54	20,63	39,45
LP evap-solar	91,62	54,108	145,728	110,5	37,13
HP pump	15,4764	14,3568	29,8296	23,9	48,12
LP pump	0,034477	0,187668	0,222156	80,09	84,48
IP pump	0,3816	1,03392	1,41552	46,13	73,05
MFH- Degasifier	24,6708	2,30436	26,9748	23,78	8,543
LP economizer	278,676	56,628	335,304	99,7	16,89
Stack	0	4,7448	4,7448	1,161	100
Feedwater pump	0,39096	0,8802	1,27116	53,86	69,26
Cooling tower	878,76	559,44	1438,56	77,79	38,9
Condenser	669,24	255,708	924,84	214,2	27,65
LP steam turbine	855	501,84	1356,84	25,11	36,98
IP steam turbine	461,52	413,64	875,16	21,48	47,26
HP steam turbine	298,152	282,24	580,32	24,84	48,63
IP solar collectors	0	136,224	136,224	Infinite	100
HP solar collectors	0	492,48	492,48	Infinite	100
LP solar collectors	0	223,524	223,524	infinite	100
GT generator	439,56	193,608	633,24	3,627	30,58
ST generator	204,768	150,66	355,464	2,465	42,39

ISCCGT Power Plant – Component Cost of Exergy Destruction and Capital Cost rate



CCGT – ISCCGT Power Plant – Levelized Cost of Electricity



CCGT – ISCCGT Power Plant – LCA Inventory Analysis – GT Inventory

Material name	Reference plant [kg]	CCGT power plant [kg]
Ferroalloys	311177	351102
Steel	242277	273362
Unalloyed steel	49248	55567
Low-alloyed steel	64897	73223
High- alloyed steel	11091	12514
Cr steel	48865	55134
Cr-Ni steel	68175	76922
Cast iron	68900	77740
Non-ferrous metal alloys	276	311
Other metals and semimetals	8	9,03
Inorganic materials , ceramics	545	615
Plastics	92	104
Miscellaneous, other materials	17	19,2
Organic materials	1219	1375

CCGT Power Plant – LCA Inventory Analysis – HRSG Inventory

HRSG component name	Unalloyed steel [kg]	Cr steel pipe [kg]	Rock wool [kg]	Total weight [kg]
Eco LP	178381,58	48391,07	6815,08	233587,73
Evap LP-gas	101472,95	27527,42	3876,78	132877,15
Sh LP	10300,56	2794,32	393,53	13488,41
Eco IP	17108,05	4641,04	653,61	22402,70
Evap IP-gas	91717,74	24881,04	3504,08	120102,87
Sh IP1	3206,76	869,92	122,51	4199,20
Sh IP	227623,04	61749,22	8696,35	298068,61
Eco HP1	184507,38	50052,87	7049,11	241609,36
Eco HP	217660,98	59046,72	8315,75	285023,45
Evap HP-gas	523875,73	142116,17	20014,69	686006,59
Sh HP	335870,57	91114,43	12831,95	439816,95
Total	1891725,35	513184,23	72273,45	2477183,02

Material needed for each section of the HRSG (CCGT power plant)

ISCCGT Power Plant – LCA Inventory Analysis – HRSG Inventory

HRSG component name	Unalloyed steel [kg]	Cr steel pipe [kg]	Rock wool [kg]	Total weight [kg]
Eco LP	190123,8	51576,5	7263,7	248963,9
Evap LP-gas	60284,7	16353,9	2303,2	78941,8
Evap LP-solar	181640,8	49275,2	6939,6	237855,6
Sh LP	16750,2	4544,0	639,9	21934,2
Eco IP	21214,3	5755,0	810,5	27779,7
Evap IP-gas	31994,5	8679,4	1222,4	41896,3
Evap IP-solar	91389,1	24791,9	3491,5	119672,5
Sh IP1	1875,1	508,7	71,6	2455,4
Sh IP	286732,1	77784,2	10954,6	375471,0
Eco HP1	195878,0	53137,5	7483,5	256499,0
Eco HP	269892,0	73215,9	10311,2	353419,1
Evap HP-gas	398575,7	108125,0	15227,6	521928,3
Evap HP-solar	313876,0	85147,8	11991,6	411015,4
Sh HP	357783,5	97058,9	13669,1	468511,6
Total	2418009,7	655953,8	92380,2	3166343,7

Material needed for each section of the HRSG (ISCCGT power plant)

CCGT – ISCCGT Power Plant – LCA Inventory Analysis

Steam turbine material inventory (larger for ISCCGT)

Material name	Reference plant [kg]	CCGT power plant [kg]	ISCCGT power plant [kg]
Ferroalloys	300904	343476	439033
Steel	214370	244699	312776
Unalloyed steel	122095	139369	178142
Low-alloyed steel	3467	3958	5059
High-alloyed steel	1571	1793	2292
Cr steel	29807	34024	43490
Cr-Ni steel	57429	65554	83792
Cast iron	86534	98777	126257

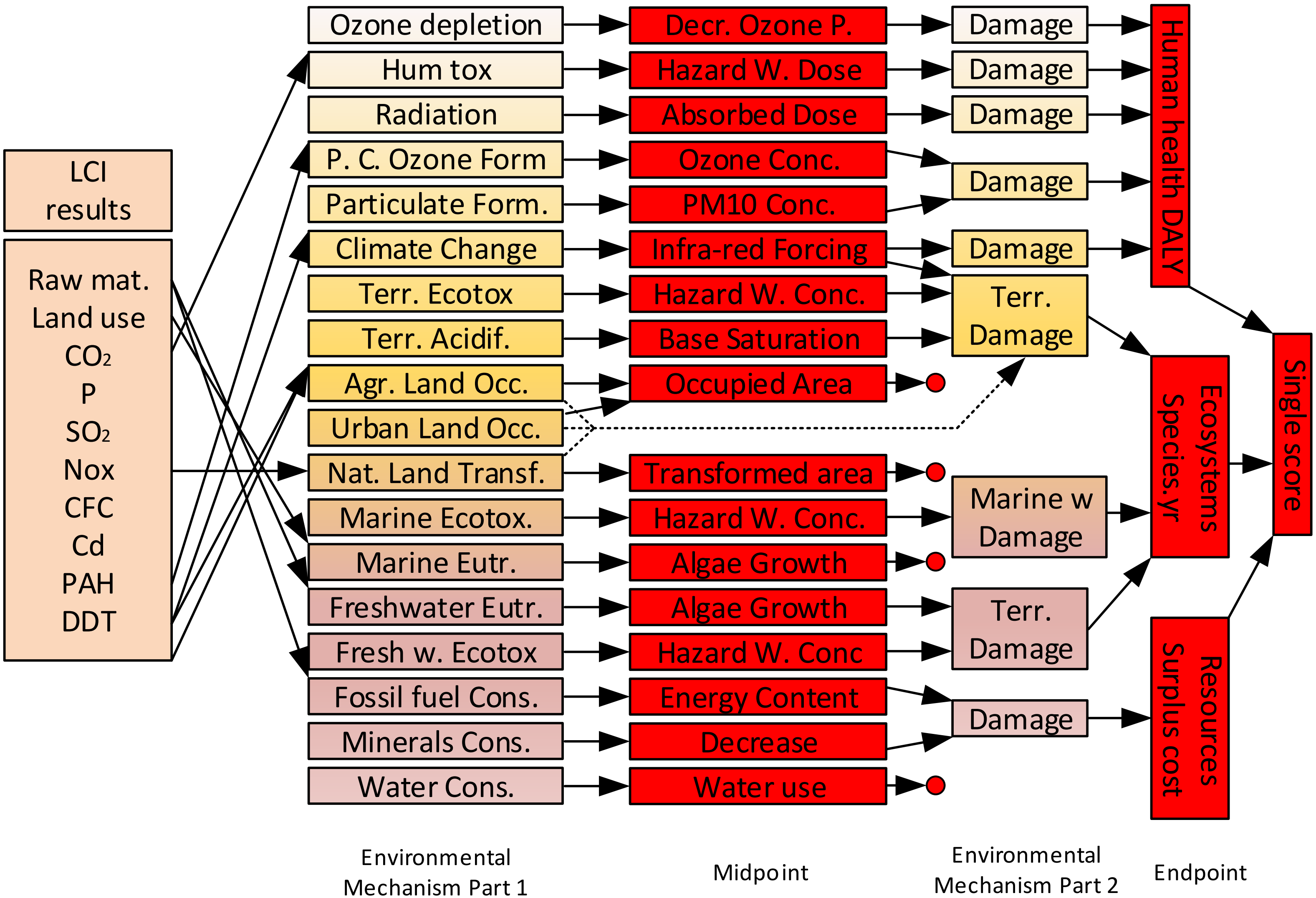
Condenser material inventory

Material name	Reference plant [kg]	CCGT power plant [kg]	ISCCGT power plant [kg]
Steel	261152	139603	178441
Unalloyed steel	212319	113498	145074
High-alloyed steel	48833	26104	33366

Cooling tower material inventory (larger for ISCCGT)

Material name	Reference plant [kg]	CCGT power plant [kg]	ISCCGT power plant [kg]
Concrete	16657182	8904378	11381606
Unalloyed steel	1850798	989375	1264622

CCGT – ISCCGT Power Plant – Recipe EndPoint

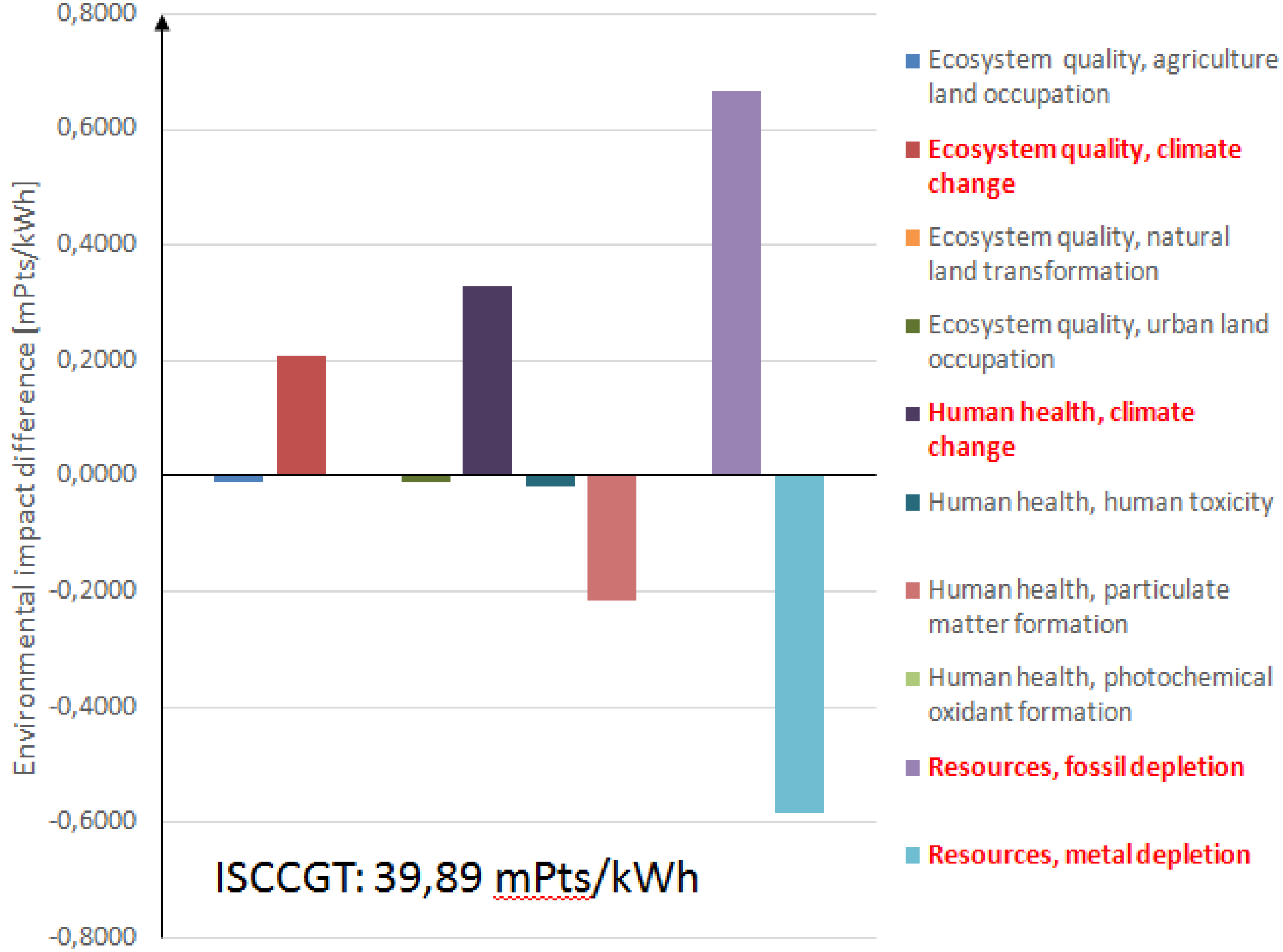


CCGT – ISCCGT Power Plant – LCA - Results

LCA

CCGT → ISCCGT

CCGT: 40,24 mPts/kWh



Environmental impact reduction by ReCiPe impact category

CCGT Power Plant

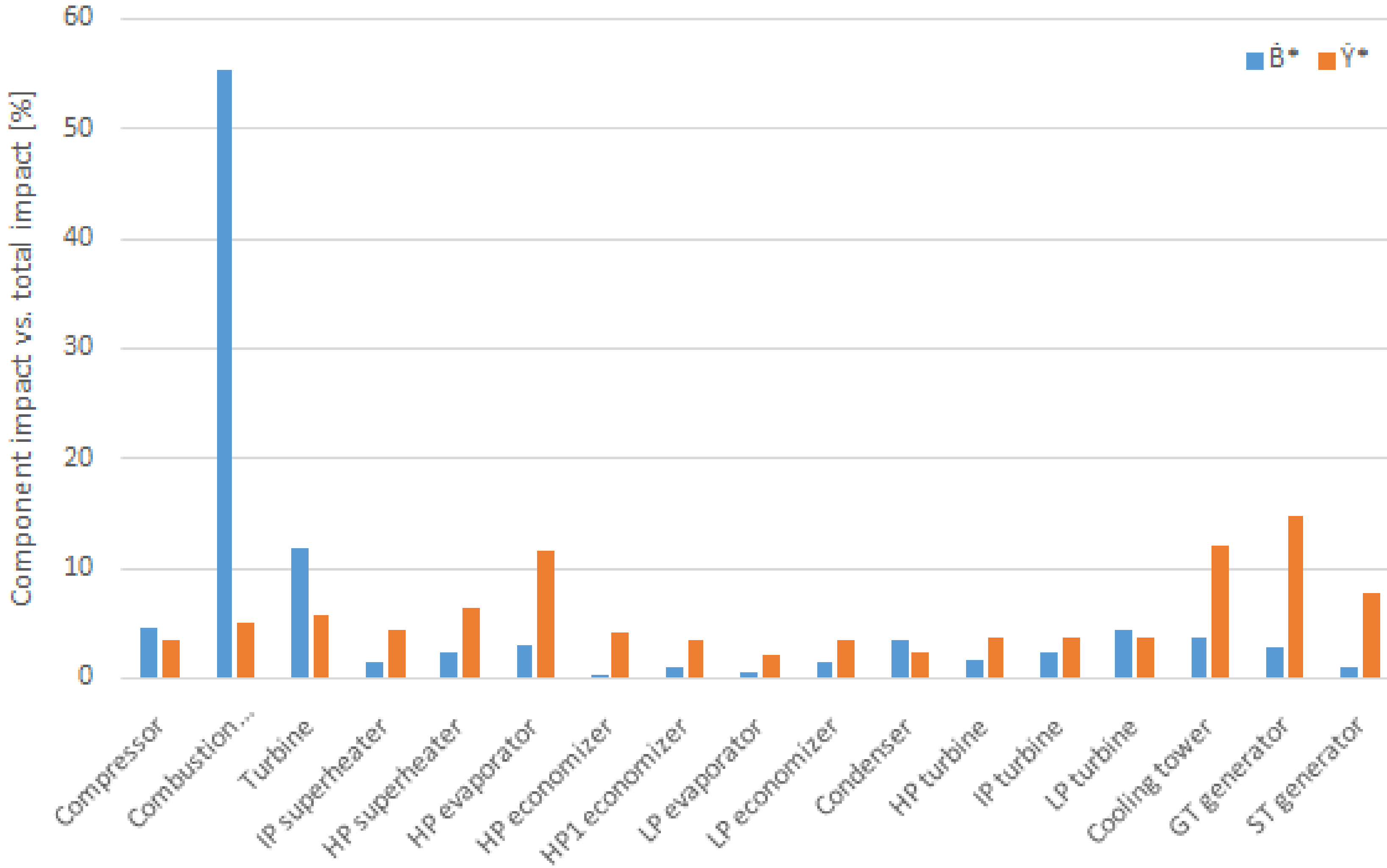
EEnvA

Exergo-Environmental Analysis

Component name	$\dot{B}_D$ [Pts·h^{-1}]	$\dot{Y}_{TOT}$ [Pts·h^{-1}]	$\dot{B}_{TOT}$ [Pts·h^{-1}]	r_b [%]	f_b [%]
Compressor	451,8	1,12968	452,88	4,787	0,2494
Combustion chamber	5421,6	1,7172	5425,2	40,52	0,03166
Turbine	1141,2	1,93392	1143,36	5,771	0,1692
IP superheater	125,208	1,46052	126,684	12,65	1,153
HP superheater	212,004	2,15568	214,164	14,76	1,007
HP evaporator	278,496	3,9528	282,456	14,09	1,399
HP economizer	30,6036	1,42344	32,0292	4,056	4,445
IP1 superheater	1,18476	0,021121	1,20564	11,84	1,752
LP superheater	6,8256	0,067608	6,894	23,35	0,9807
IP evaporator	16,2324	0,59904	16,8336	5,672	3,56
IP economizer	14,922	0,126936	15,048	40,78	0,8435
HP1 economizer	79,38	1,19412	80,568	16,81	1,482
LP evaporator	35,6904	0,6642	36,36	16,24	1,827
IP pump	0,16704	0,00607	0,173124	12,84	3,506
LP pump	0,008424	0,000305	0,008726	12,85	3,496
HP pump	7,0776	0,224172	7,3008	12,75	3,071
Deaerator	6,3252	0,083556	6,408	24,14	1,304
LP economizer	140,652	1,17036	141,84	65,16	0,8251
Feedwater pump	0,17046	0,005026	0,1755	17,05	2,864
Stack	0	0,113256	0,113256	0,03857	100
Condenser	325,692	0,79884	326,484	155,4	0,2447
HP turbine	150,876	1,24236	152,136	11,39	0,8165
IP turbine	227,916	1,24236	229,176	10,41	0,542
LP turbine	410,04	1,24236	411,48	15,24	0,302
Cooling tower	347,58	4,0968	351,684	48,09	1,165
GT generator	271,152	5,058	276,192	2,565	1,832

CCGT Power Plant

Environmental impacts : Exergy Destruction and Component –related



IS CCGT Power Plant

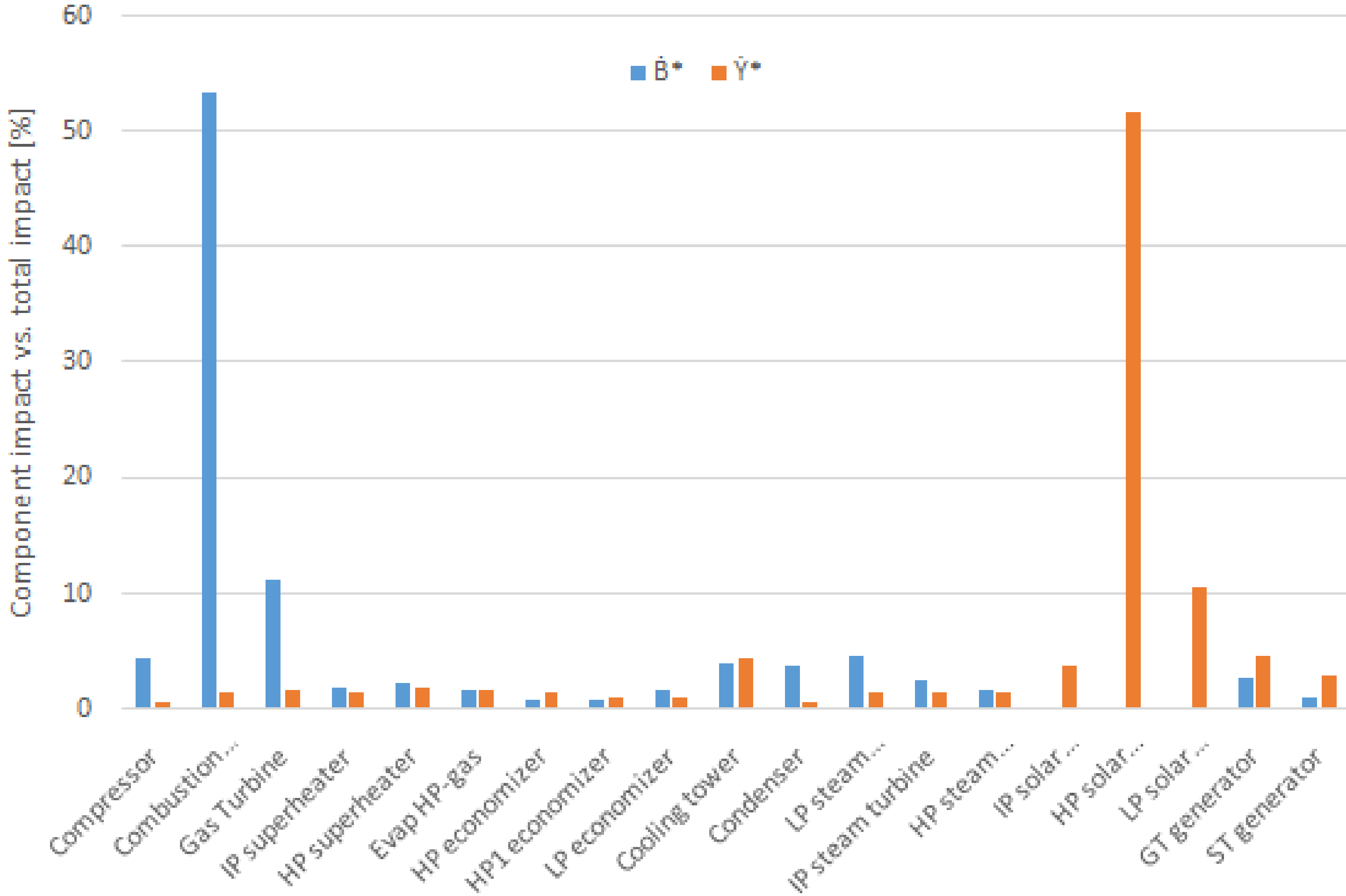
EEnvA

Exergo-Environmental Analysis

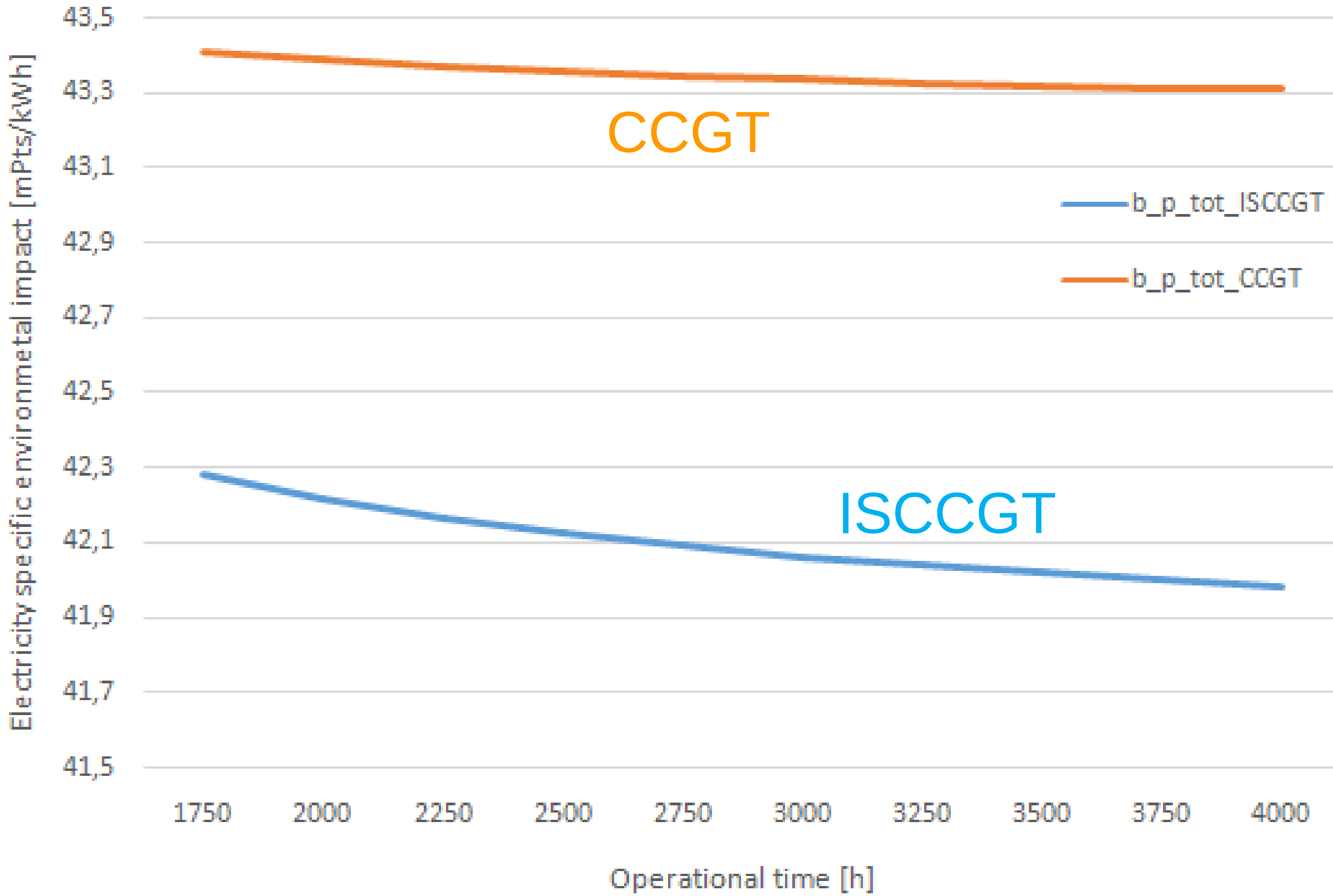
Component name	$\dot{B}_D$ [Pts·h^{-1}]	$\dot{Y}_{TOT}$ [Pts·h^{-1}]	$\dot{B}_{TOT}$ [Pts·h^{-1}]	f_b [%]	r_b [%]
Compressor	477,72	0,78696	478,44	0,1644	4,783
Combustion chamber	5734,8	1,66644	5734,8	0,02905	40,52
Gas Turbine	1206,72	1,77156	1208,52	0,1466	5,769
IP superheater	214,848	1,728	216,576	0,7979	16,19
HP superheater	261,432	2,1564	263,592	0,818	46,85
Evap HP-solar	16,146	1,8918	18,0396	10,49	43,67
Evap HP-gas	182,088	1,9044	183,996	1,035	10,79
HP economizer	92,448	1,64016	94,104	1,743	9,314
IP1 superheater	0,358344	0,0113	0,36972	3,057	5,541
LP superheater	11,4192	0,10476	11,5236	0,909	22,61
IP Evaporator-gas	4,8456	0,192816	5,04	3,827	4,496
IP Evaporator -solar	1,7622	0,5508	2,313	23,81	89,12
IP economizer	11,4372	0,127836	11,5668	1,105	23,59
HP1 economizer	96,084	1,18044	97,272	1,214	17,95
LP evap-gas	18,3708	0,36324	18,7344	1,939	12,74
LP evap-solar	4,8456	1,09476	5,94	18,43	85,17
HP pump	8,3664	0,28116	8,6472	3,252	12,82
LP pump	0,018637	0,000721	0,019357	3,726	12,91
IP pump	0,206244	0,007978	0,214236	3,725	12,92
Deaerator	8,1072	0,042048	8,1504	0,516	21,86
LP economizer	185,724	1,14588	186,876	0,6132	83,37
Stack	0	0,113256	0,113256	100	0,04157
CEP	0,211248	0,006361	0,21762	2,924	17,06
Cooling tower	427,68	4,9644	432,72	1,147	48,08
Condenser	401,04	0,75708	401,76	0,1885	155,3
LP steam turbine	504	1,59768	505,8	0,316	15,87
IP steam turbine	274,752	1,59768	276,372	0,5782	11,4
HP steam turbine	180,036	1,59768	181,62	0,8797	12,87
IP solar collectors	0	4,3596	4,3596	100	infinite
HP solar collectors	0	57,456	57,456	100	infinite
LP solar collectors	0	11,8188	11,8188	100	infinite
GT generator	286,704	5,112	291,816	1,752	2,563

IS CCGT Power Plant

Environmental impacts: Exergy Destruction and Component – related



CCGT – ISCCGT Power Plant – Levelized Environmental Cost of Electricity



CCGT – ISCCGT Power Plant

Resource (NG) savings and avoided CO2 Emissions