Technische Universität Berlin
Institute for Energy Engineering

Thermoeconomic Analysis

Tutorial

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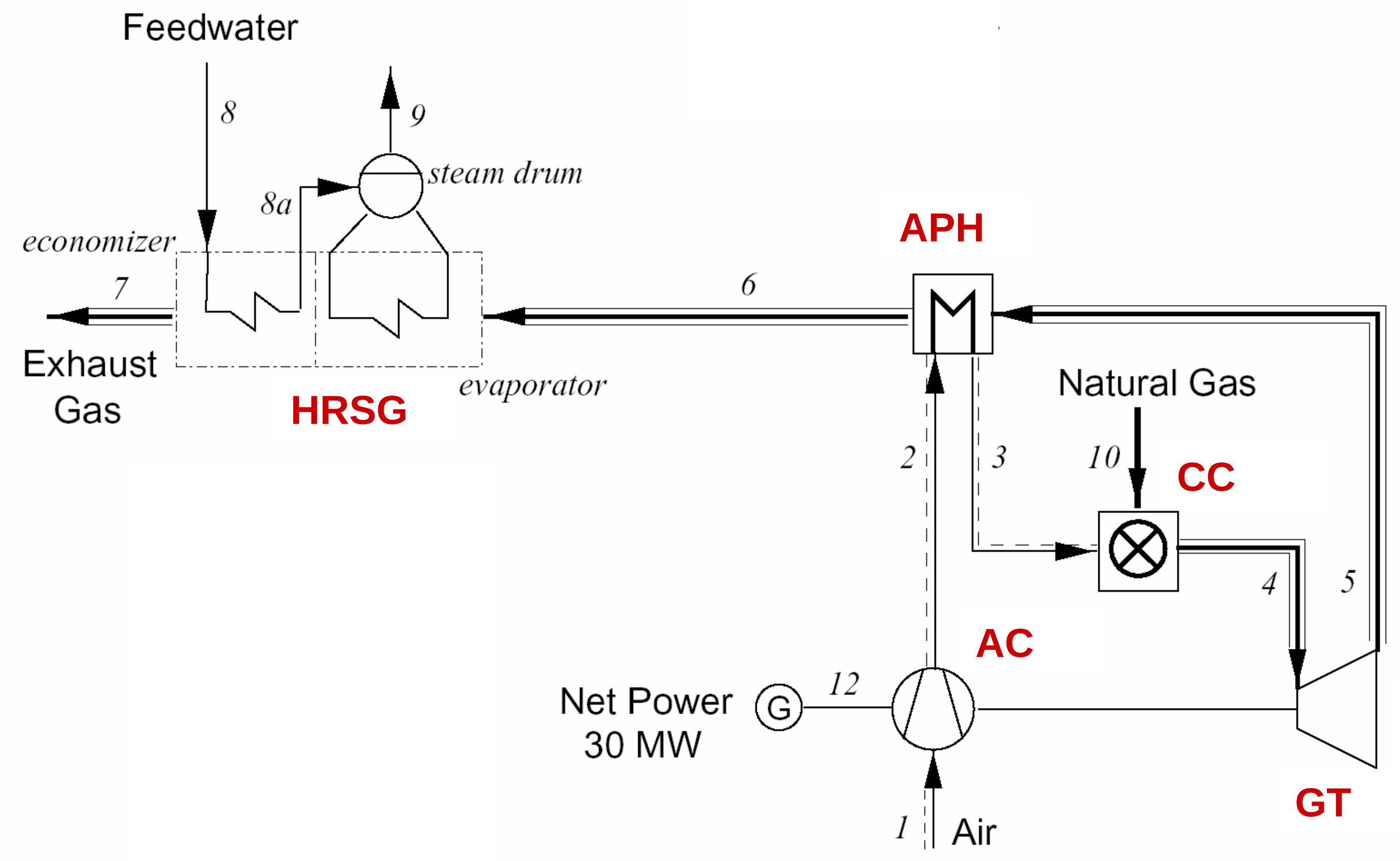
Study Case: Cogeneration System



Economic Analysis

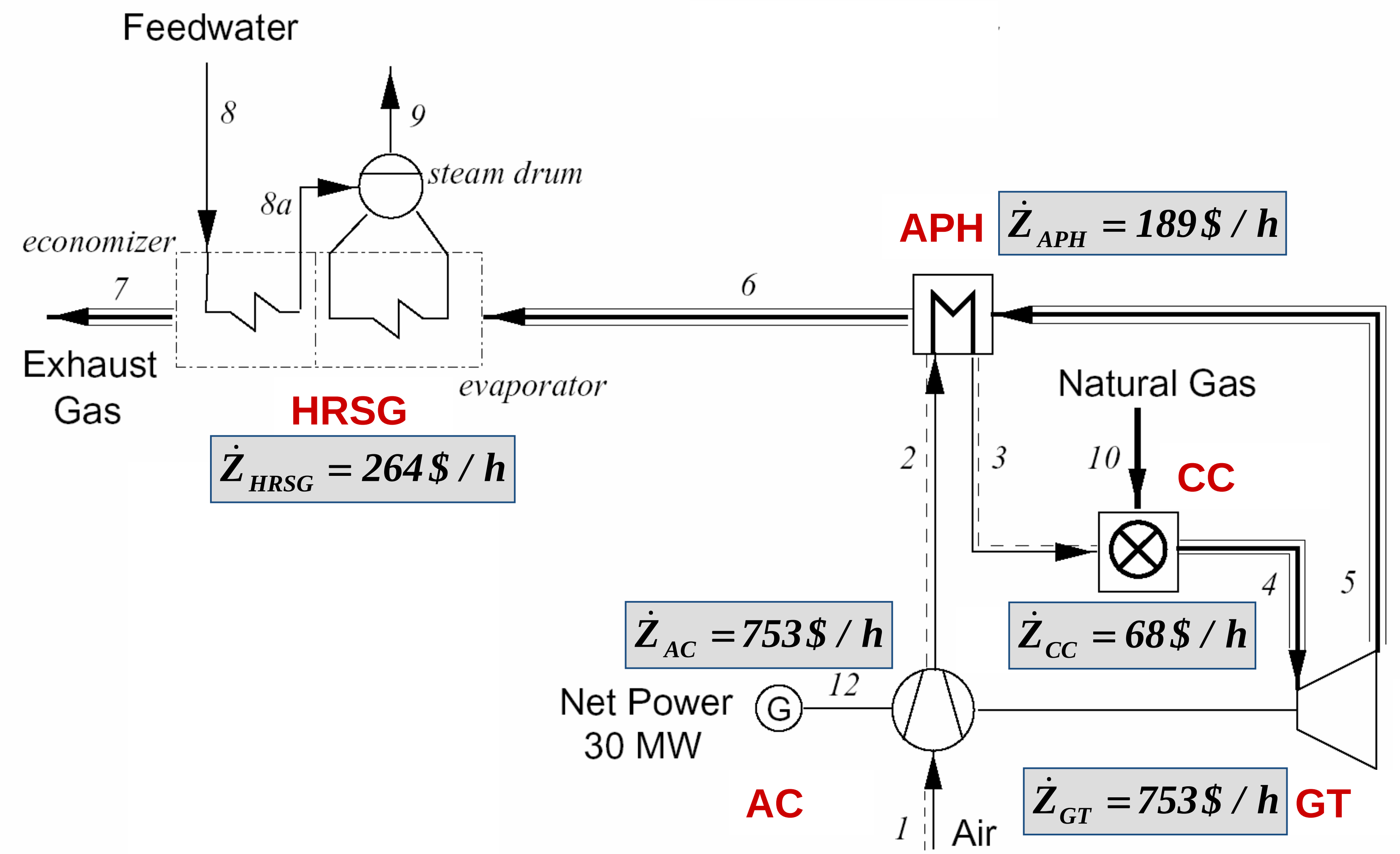
Purchased-equipment costs **for each component in the base-case design are obtained from the cost equations.**

The remaining *direct costs*, as well as the *indirect costs*, are estimated using average factors. The total capital investment of the cogeneration system in the base case is estimated at approximately *46 million mid-1994 dollars*.

The parameters and assumptions used in the economic analysis, which is based on the revenue-requirement method.

The year-by-year economic analysis results in the levelized annual costs for fuel ($\$10.4 \times 10^6$), operating and maintenance ($\$5.9 \times 10^6$) and carrying charges ($\$10.5 \times 10^6$) for a levelization time period of 10 years.

Capital Investment Cost

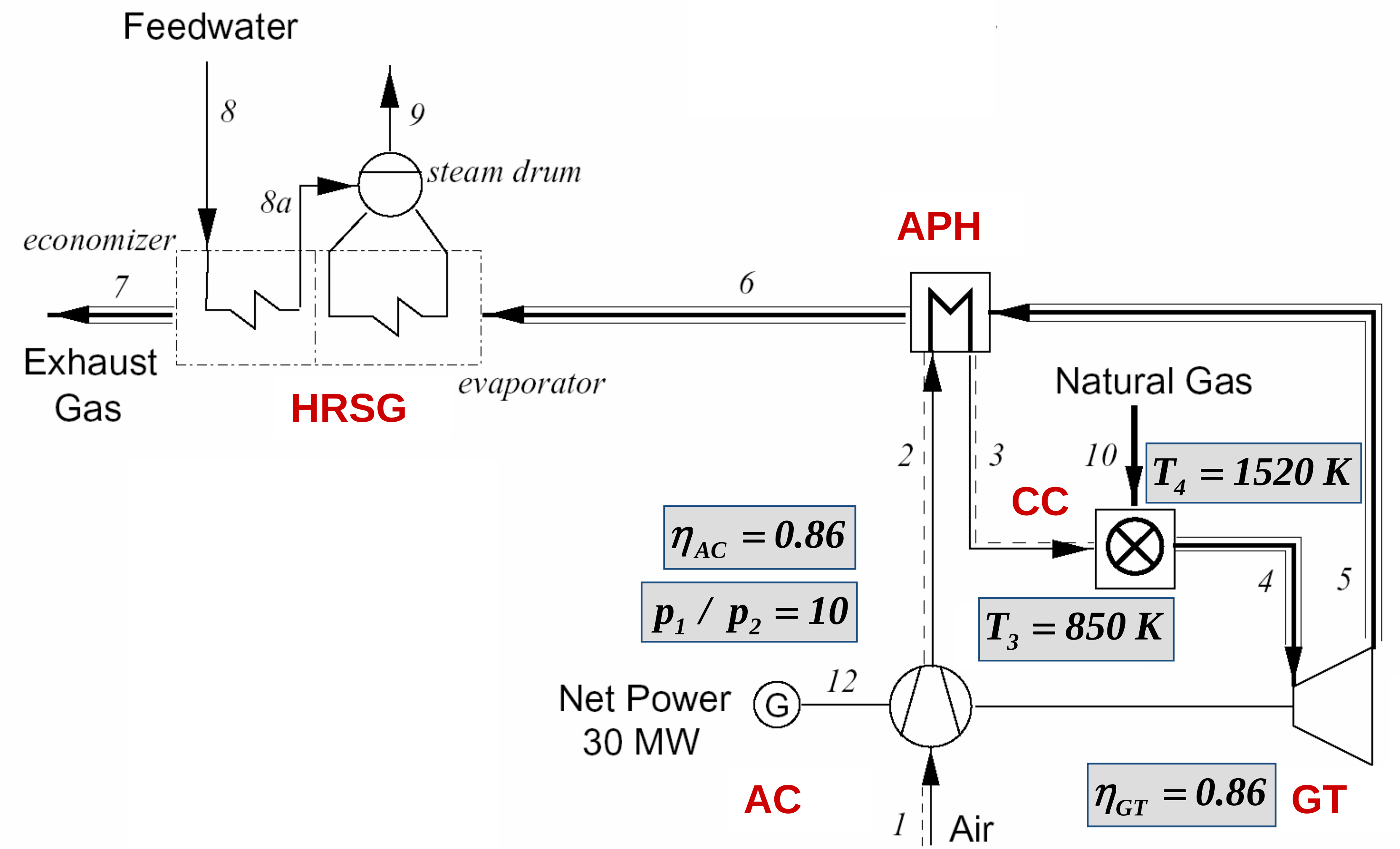


Thermodynamic Analysis

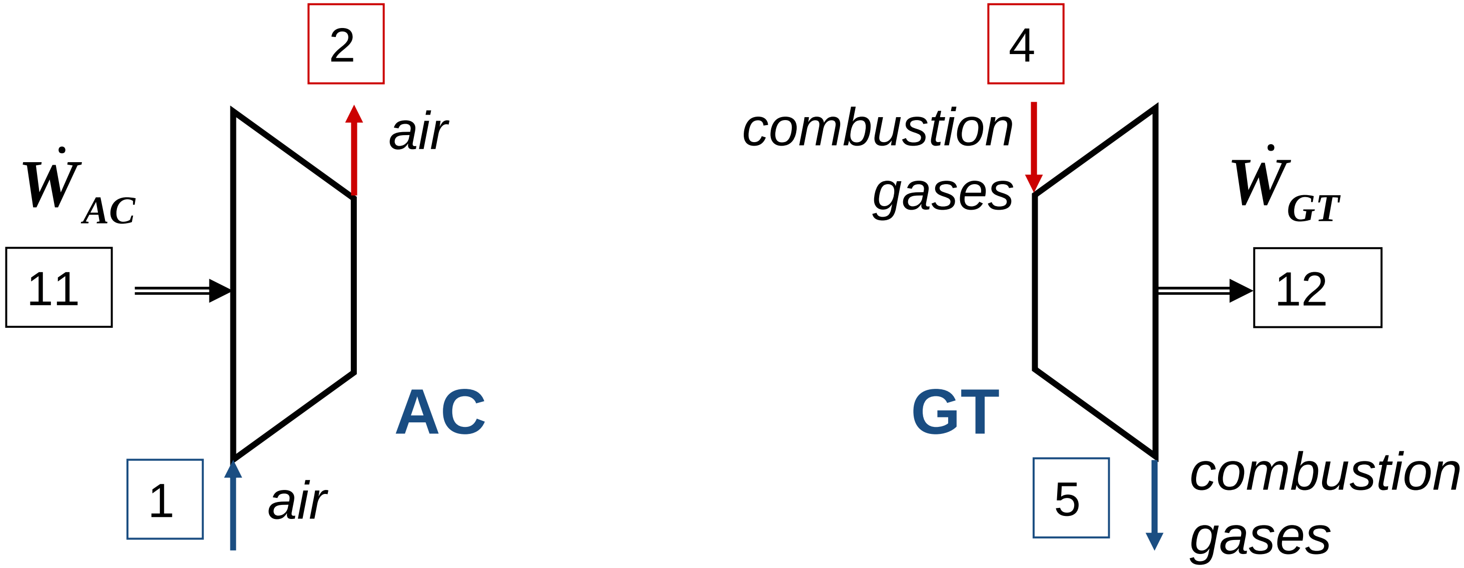
The objective is to identify the effects of the design variables on the costs and suggest values of the design variables that would make the system more cost effective. The key design variables - *the decision variables* - for the cogeneration system are

- **the compressor pressure ratio** p_2 / p_1
- **the isentropic compressor efficiency** η_{AC}
- **the isentropic turbine efficiency** η_{GT}
- **the temperature of the air entering the combustion chamber** T_3
- **the temperature of the combustion products entering the gas turbine** T_4

Thermodynamic Data



Exergoeconomic Analysis: AC and GT



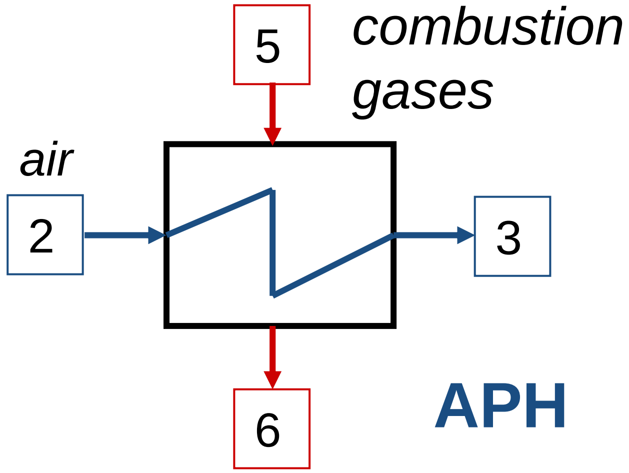
$$\dot{E}_2 - \dot{E}_1 = \dot{W}_{AC} - \dot{E}_{D,AC}$$

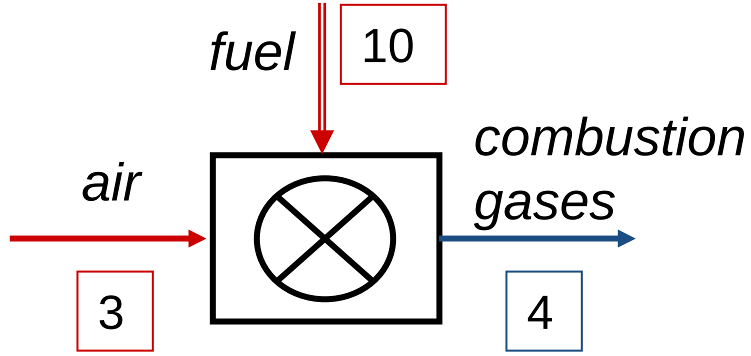
$$c_2\dot{E}_2 - c_1\dot{E}_1 = \dot{Z}_{CM} + c_{11}\dot{E}_{11}$$

$$\dot{W}_{GT} = \left(\dot{E}_2 - \dot{E}_1\right) - \dot{E}_{D,GT}$$

$$c_{12}\dot{E}_{12} = \dot{Z}_{CM} + \left(c_4\dot{E}_4 - c_5\dot{E}_5\right)$$

Exergoeconomic Analysis: APH and CC





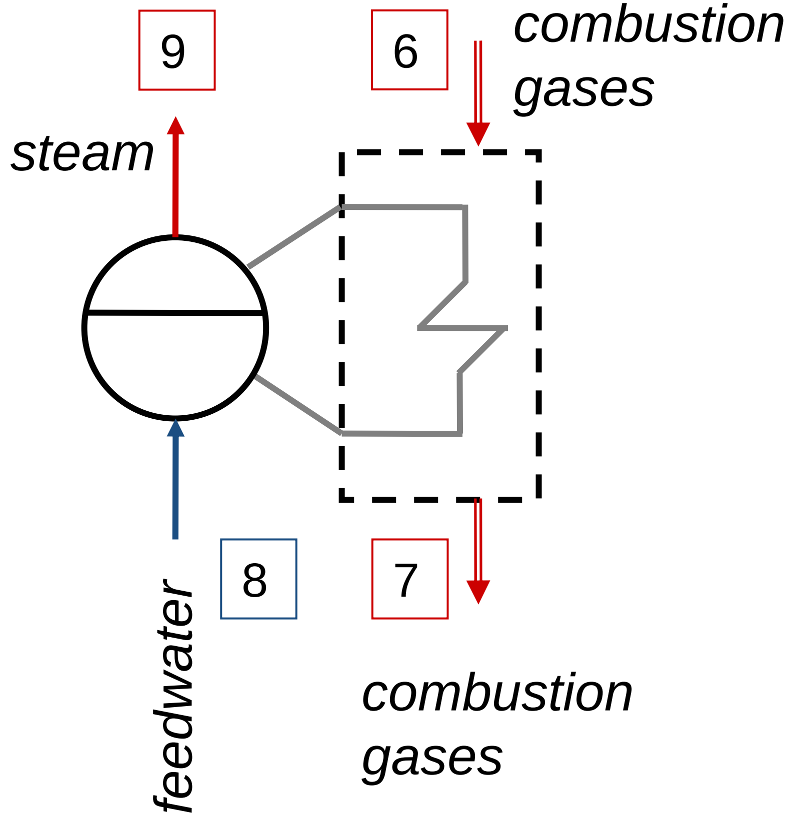
$$\left(\dot{E}_3 - \dot{E}_2\right) = \left(\dot{E}_5 - \dot{E}_6\right) - \dot{E}_{D,APH}$$

$$\left(\dot{E}_4 - \dot{E}_3\right) = \dot{E}_{10} - \dot{E}_{D,CC}$$

$$\left(\dot{C}_2 - \dot{C}_1\right) = \dot{Z}_{HE} + \left(\dot{C}_3 - \dot{C}_4\right)$$

$$\left(\dot{C}_4 - \dot{C}_3\right) = \dot{Z}_{CC} + \dot{C}_{10}$$

Exergoeconomic Analysis: HRSG



$$\dot{E}_9 - \dot{E}_8 = \left(\dot{E}_6 - \dot{E}_7\right) - \dot{E}_{D,HRSG}$$

$$\dot{C}_9 - \dot{C}_8 = \dot{Z}_{HRSG} + \left(\dot{C}_6 - \dot{C}_7\right)$$

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

Exergoeconomic Analysis – Base Case

Values of the purchased-equipment costs (PEC) and the exergoeconomic variables

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.

Exergoeconomic Analysis – Base Case

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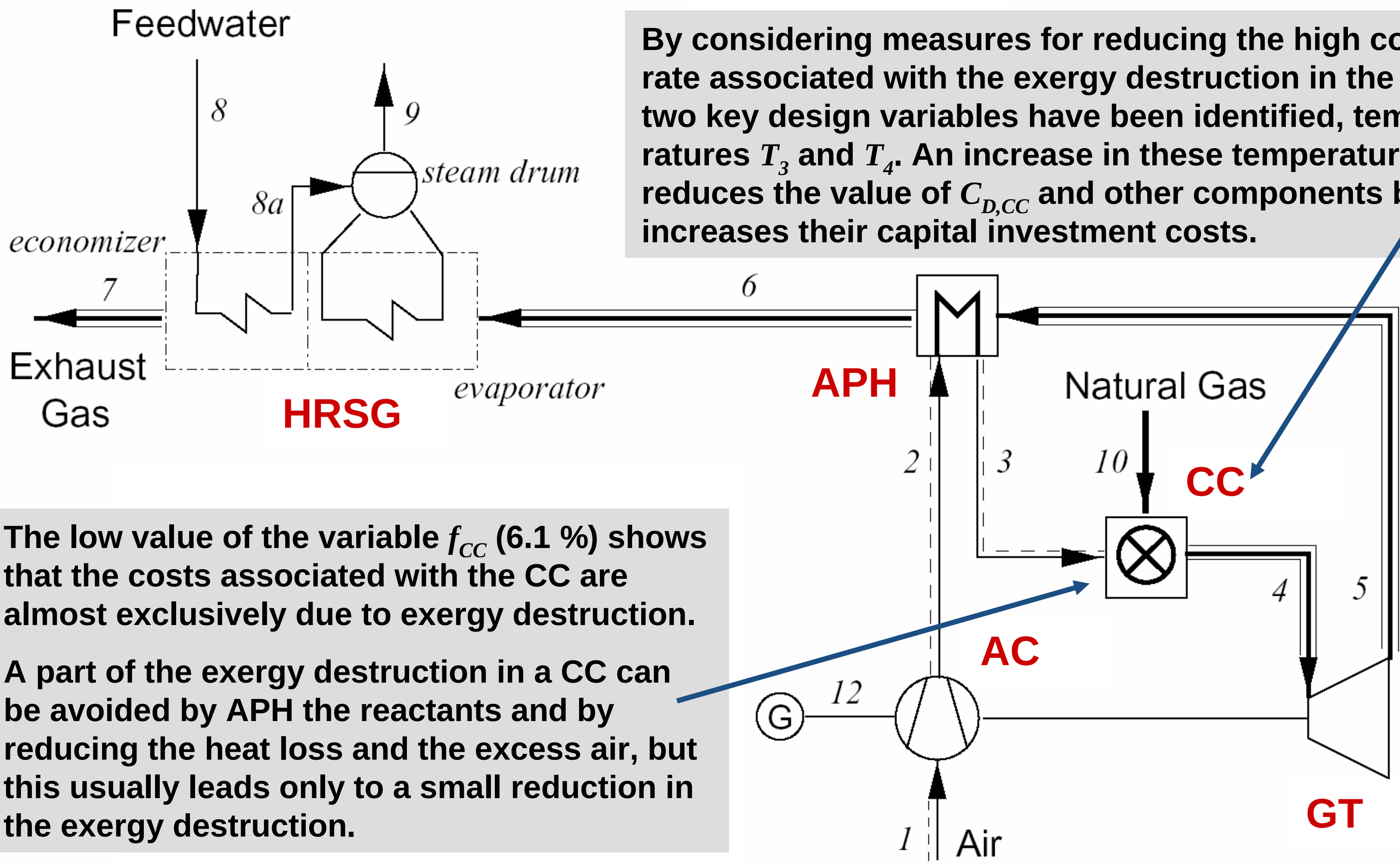
The *Combustion Chamber*, the *Gas Turbine*, and the *Air Compressor* have the highest values of the sum (Z_k + $C_{D,k}$) and are, therefore, the most important components from the thermoeconomic viewpoint.

Exergoeconomic Analysis – Base Case

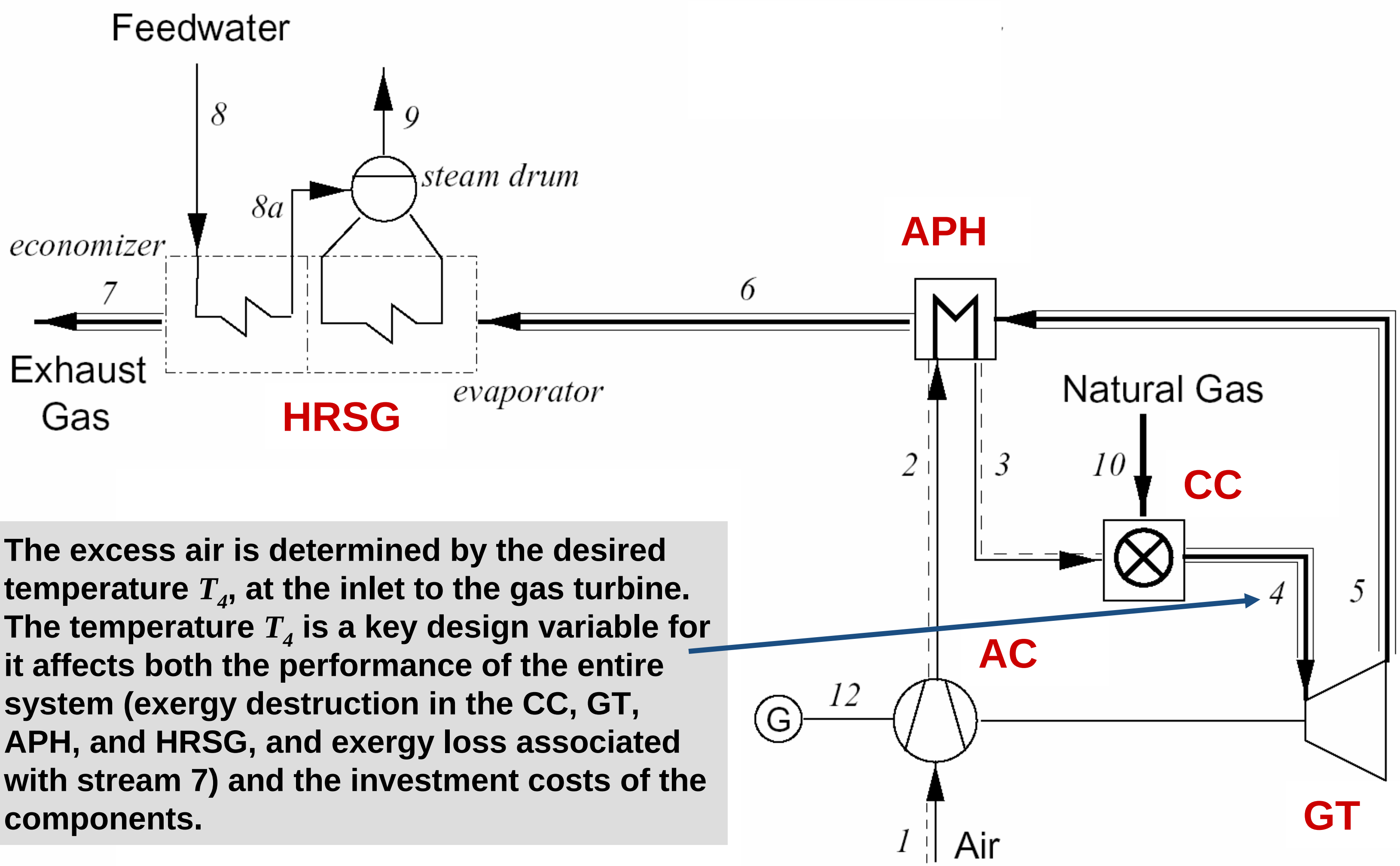
By considering measures for reducing the high cost rate associated with the exergy destruction in the CC, two key design variables have been identified, temperatures T_3 and T_4. An increase in these temperatures reduces the value of $C_{D,CC}$ and other components but increases their capital investment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

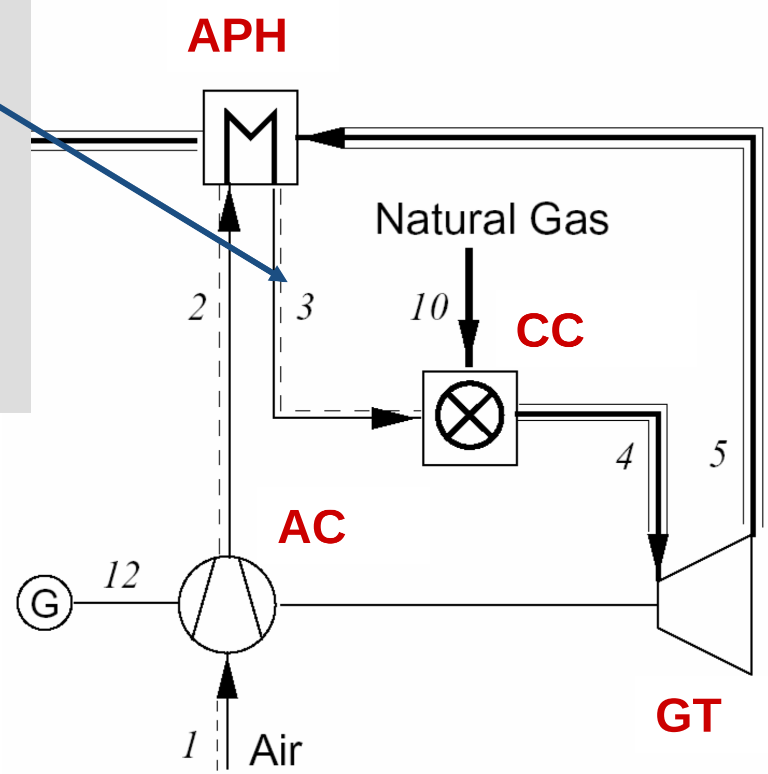
Exergoeconomic Analysis – Base Case



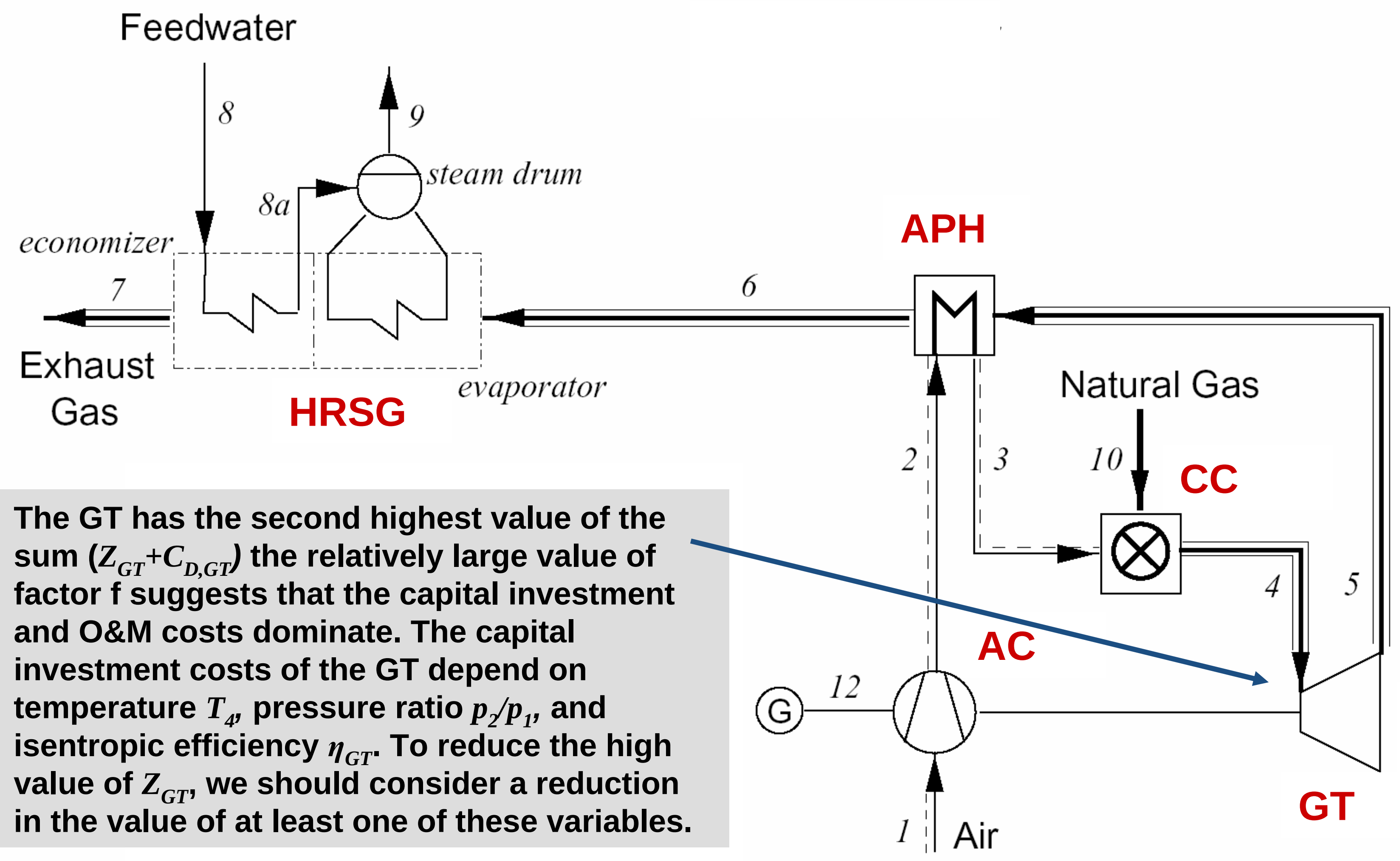
The excess air is determined by the desired temperature T_4, at the inlet to the gas turbine. The temperature T_4 is a key design variable for it affects both the performance of the entire system (exergy destruction in the CC, GT, APH, and HRSG, and exergy loss associated with stream 7) and the investment costs of the components.

Exergoeconomic Analysis – Base Case

An increase in the heat transfer rate in the APH achieved through an increase in T_3 also results in a decrease of the exergy destruction in the CC. Thus, the temperature T_3 is also a key design variable because, in addition to the CC, it affects the exergy loss associated with stream 7 as well as the performance and investment costs of the APH and the HRSG. The higher the T_3 the smaller the average temperature difference in the APH and the HRSG. A decrease in the average temperature difference in APH and HRSG results in an increase in both the exergetic efficiency and the capital investment for APH and HRSG.

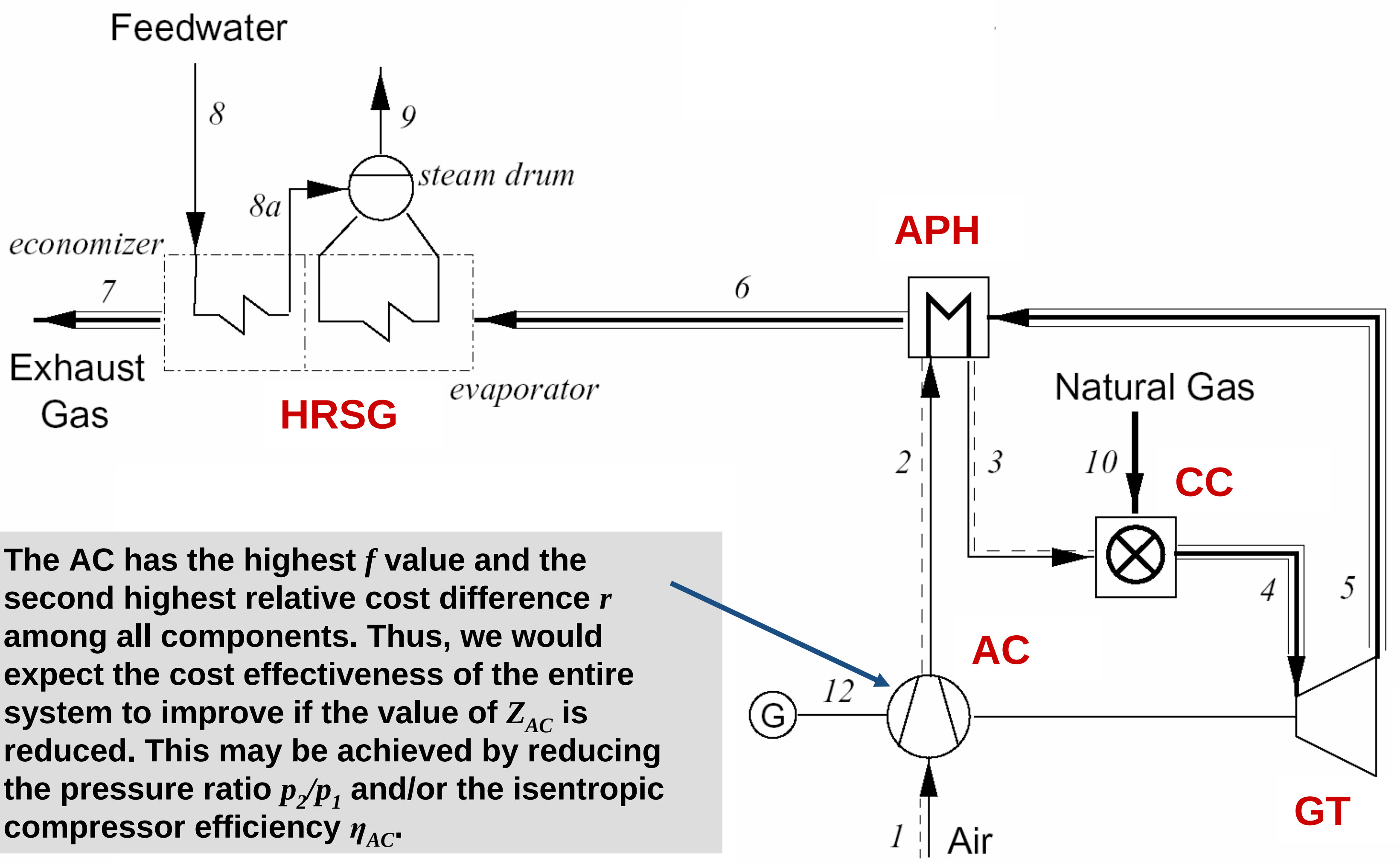


Exergoeconomic Analysis – Base Case



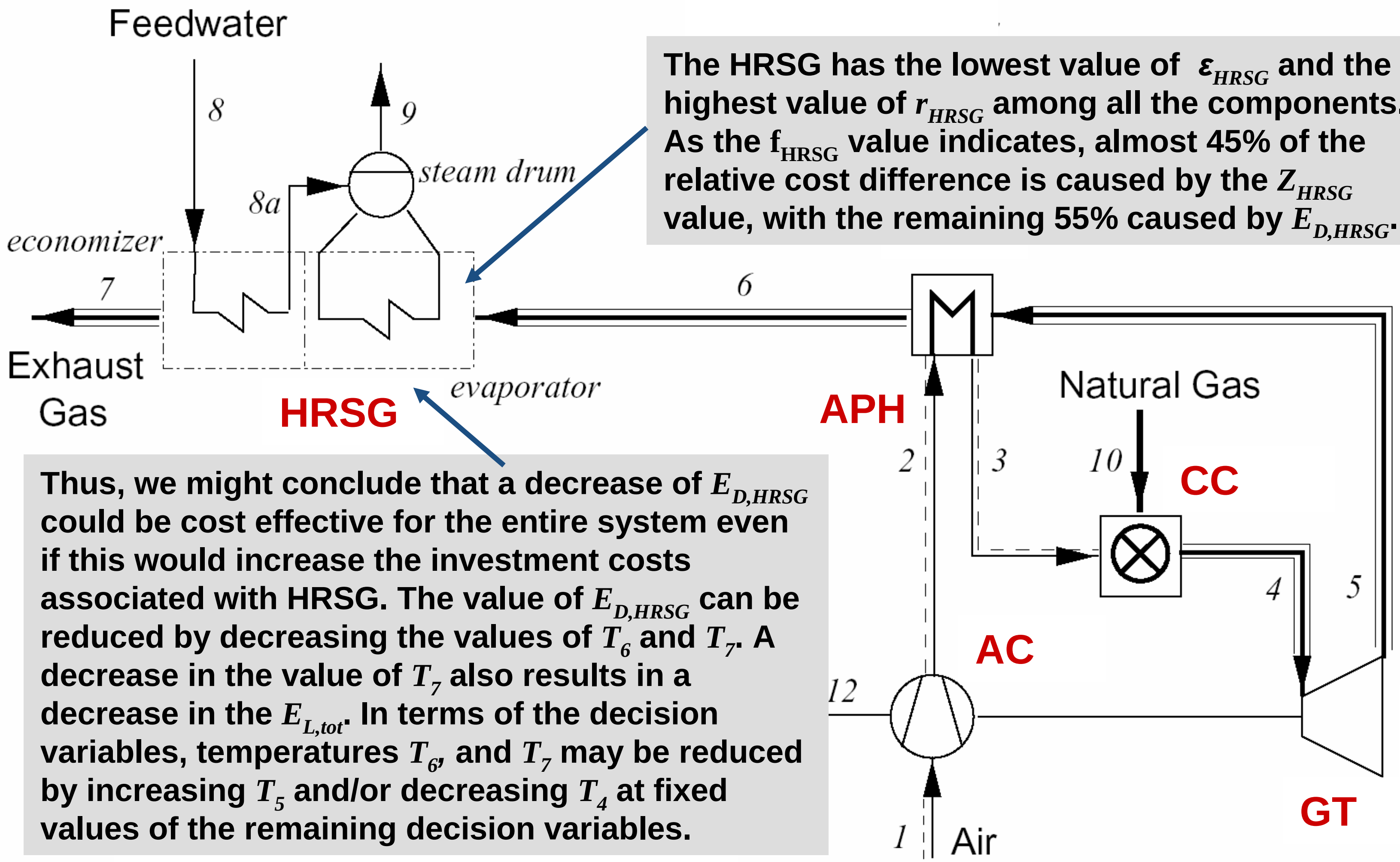
The GT has the second highest value of the sum (Z_{GT}+$C_{D,GT}$) the relatively large value of factor f suggests that the capital investment and O&M costs dominate. The capital investment costs of the GT depend on temperature T_4, pressure ratio p_2/p_1, and isentropic efficiency η_{GT}. To reduce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

Exergoeconomic Analysis – Base Case



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}.

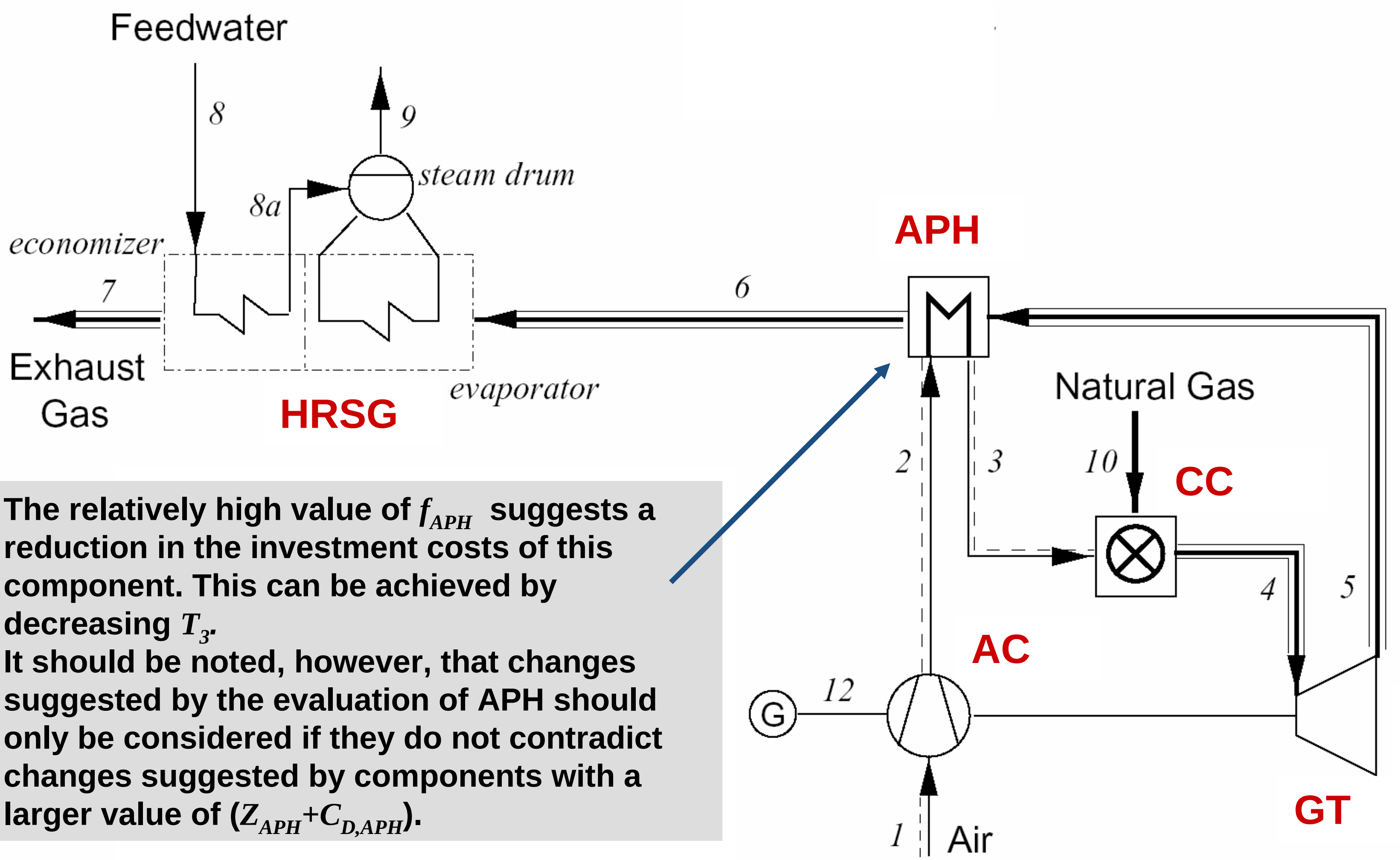
Exergoeconomic Analysis – Base Case



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 $E_{D,HRSG}$.

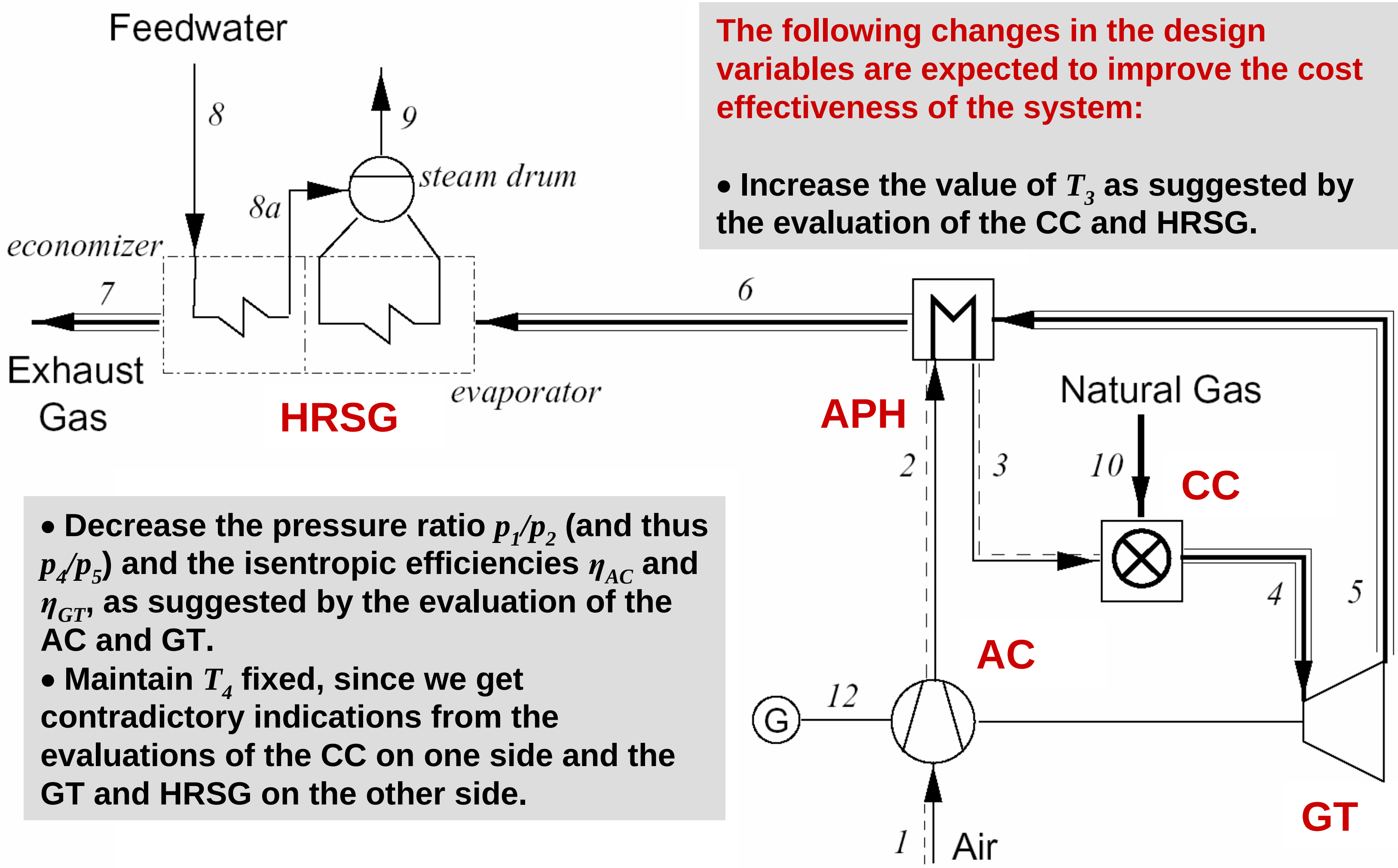
Thus, we might conclude that a decrease of $E_{D,HRSG}$ could be cost effective for the entire system even if this would increase the investment costs associated with HRSG. The value of $E_{D,HRSG}$ can be reduced by decreasing the values of T_6 and T_7. A decrease in the value of T_7 also results in 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.

Exergoeconomic Analysis – Base Case



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 ($Z_{APH}+C_{D,APH}$).

Exergoeconomic Analysis – Base Case



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.**

Thermodynamic Data: First Iteration

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

Exergoeconomic Analysis – First Iteration

Component	ε [%]	$\dot{E}_D$ [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	**80.4**	**25.48**	**29.98**	**11.45**	**14.51**	**1050**	**68**	**1118**	**26.7**	**6.1**
	80.3	25.93	29.77	10.50	13.26	980	72	1052	26.3	6.8
Gas Turbine	**95.2**	**3.01**	**3.54**	**14.51**	**18.76**	**157**	**753**	**910**	**29.2**	**82.7**
	94.9	3.18	3.66	13.26	16.97	152	647	799	28.0	81.0
Air Compressor	**92.8**	**2.12**	**2.50**	**18.76**	**27.80**	**143**	**753**	**896**	**48.2**	**84.0**
	92.1	2.34	2.69	16.97	23.96	143	546	689	41.2	79.2
HRSG	**67.2**	**6.23**	**7.33**	**14.51**	**27.36**	**326**	**264**	**590**	**88.5**	**44.8**
	66.6	6.40	7.35	13.26	25.60	305	261	566	93.1	46.1
Air Preheater	**84.6**	**2.63**	**3.09**	**14.51**	**20.81**	**137**	**189**	**326**	**43.4**	**57.9**
	84.7	3.15	3.62	13.26	18.94	150	206	365	42.9	57.8

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

For the overall plant (First iteration): $C_{P,tot}$=$3355/h and $C_{L,tot}=C_7$=$157/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 still the most important components from the thermoeconomic viewpoint.

Exergoeconomic Analysis – First Iteration

Component	ε [%]	$\dot{E}_D$ [MW]	y_D [%]	c_F [$/GJ]	c_P [$/GJ]	$\dot{C}_D$ [$/GJ]	$\dot{Z}$ [$/GJ]	$\dot{C}_D + \dot{Z}$ [$/GJ]	r [%]	f [%]
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The high cost rate associated with the CC can be reduced by increasing the values of T_3 and T_4. In the evaluation of the cogeneration system we should, however, consider that the value of (Z_{CC}+$C_{D,CC}$) will always be the highest among all values for the components of the cogeneration system.

Exergoeconomic Analysis – First Iteration

Component	ε [%]	$\dot{E}_D$ [MW]	y_D [%]	c_F [$/GJ]	c_P [$/GJ]	$\dot{C}_D$ [$/GJ]	$\dot{Z}$ [$/GJ]	$\dot{C}_D + \dot{Z}$ [$/GJ]	r [%]	f [%]
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The GT now has the highest f value. The reduction in this value from 82.7% in the base design to 81.0% in the new design is relatively small. This observation suggests:

(a) a significant decrease in the values of η_{GT} and/or p_2/p_1 - that is, a decrease that is greater than the decrease in these variables in the previous step: from 86% to 85·% and from 10 to 9, respectively, and

(b) a reduction in the values of T_4. Note that the decrease in T_4 value contradicts the corresponding suggestion from the combustion chamber.

Exergoeconomic Analysis – First Iteration

Component	ε [%]	$\dot{E}_D$ [MW]	y_D [%]	c_F [$/GJ]	c_P [$/GJ]	$\dot{C}_D$ [$/GJ]	$\dot{Z}$ [$/GJ]	$\dot{C}_D+\dot{Z}$ [$/GJ]	r [%]	f [%]
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AC: The high values of f_{AC} and the relative cost difference r_{AC} suggest a decrease in the values of the decision variables p_2/p_1 and η_{AC}.

APH: The relatively high value of f_{APH} suggests a reduction in the T_3 value. As noted in the first iteration, however, changes suggested by the evaluation of APH should only be considered if they do not contradict changes suggested by components with a higher value of the sum ($Z_{APH}+C_{D,APH}$).

Exergoeconomic Analysis – First Iterations

Component	ε [%]	$\dot{E}_D$ [MW]	y_D [%]	c_F [$/GJ]	c_P [$/GJ]	$\dot{C}_D$ [$/GJ]	$\dot{Z}$ [$/GJ]	$\dot{C}_D + \dot{Z}$ [$/GJ]	r [%]	f [%]
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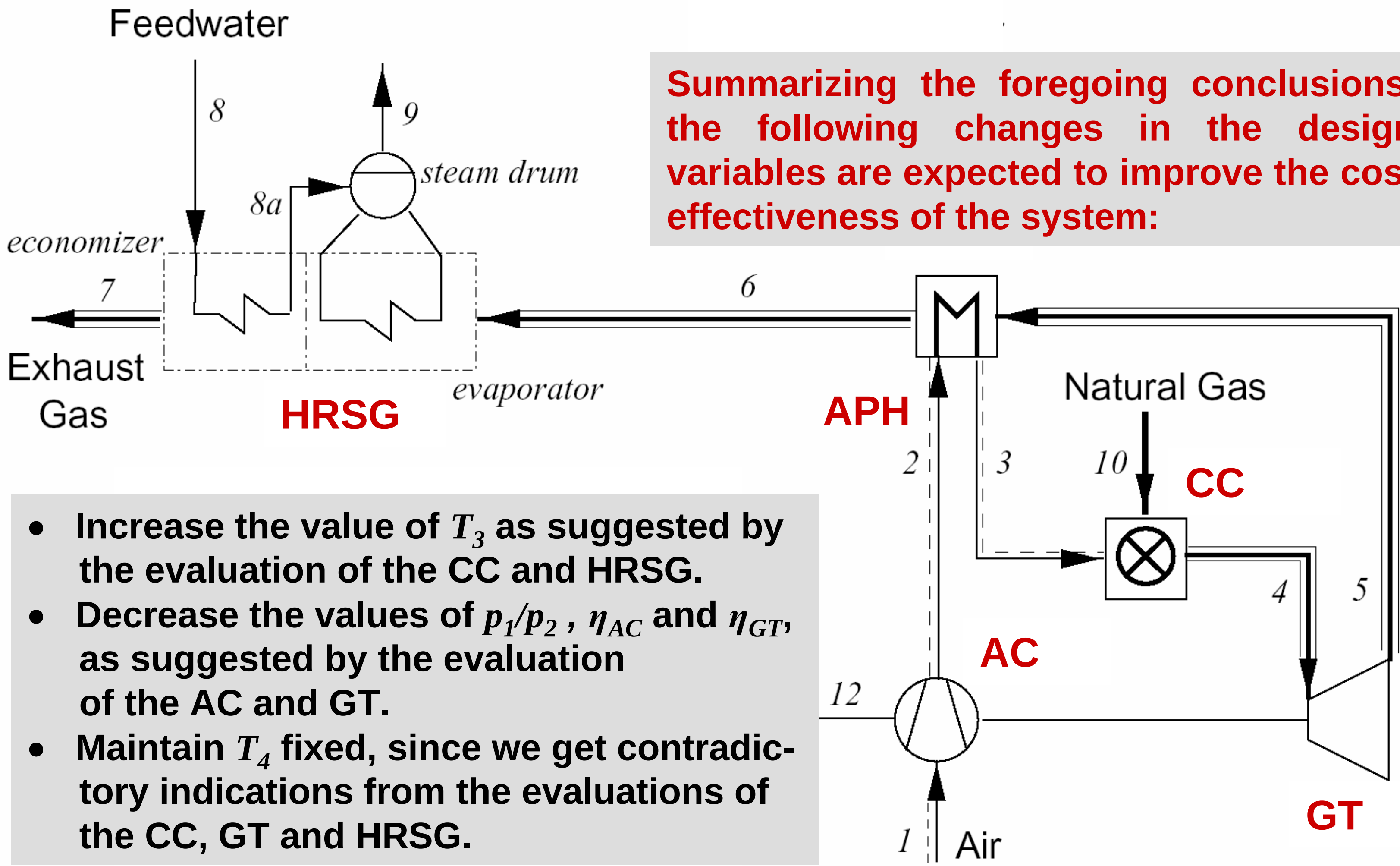
Air Compressor	**92.8**	**2.12**	**2.50**	**18.76**	**27.80**	**143**	**753**	**896**	**48.2**	**84.0**
	92.1	2.34	2.69	16.97	23.96	143	546	689	41.2	79.2
HRSG	**67.2**	**6.23**	**7.33**	**14.51**	**27.36**	**326**	**264**	**590**	**88.5**	**44.8**
	66.6	6.40	7.35	13.26	25.60	305	261	566	93.1	46.1
Air Preheater	**84.6**	**2.63**	**3.09**	**14.51**	**20.81**	**137**	**189**	**326**	**43.4**	**57.9**
	84.7	3.15	3.62	13.26	18.94	150	206	365	42.9	57.8

The anticipated increase in the exergetic efficiency of the HRSG (comparing with the Base Case) was not realized because of the interdependence of the components: The reduction in the values of p_2/p_1, η_{GT} and η_{AC} leads to an increase in the temperature differences (and therefore a decrease in the exergetic efficiency) of the HRSG. Thus, the HRSG thermoeconomic evaluation suggests that the T_3 value increases and the T_4 value decreases.

Exergoeconomic Analysis – First Iterations



Summarizing the foregoing conclusions, 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 values of p_1/p_2 , 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, GT and HRSG.**

Thermodynamic Data: Second Iteration

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

$p_1 / p_2 = 7$ | $\eta_{AC} = 0.83$ | $\eta_{GT} = 0.83$ | $T_3 = 910\ K$ | $T_4 = 1480\ K$

Exergoeconomic Analysis – Second Iterations

Component	ε [%]	$\dot{E}_D$ [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	**80.4**	**25.48**	**29.98**	**11.45**	**14.51**	**1050**	**68**	**1118**	**26.7**	**6.1**
	80.3	25.93	29.77	10.50	13.26	980	72	1052	26.3	6.8
	81.3	27.47	29.92	9.42	11.71	931	55	986	24.4	5.5
Gas Turbine	**95.2**	**3.01**	**3.54**	**14.51**	**18.76**	**157**	**753**	**910**	**29.2**	**82.7**
	94.9	3.18	3.66	13.26	16.97	152	647	799	28.0	81.0
	94.3	3.69	4.01	11.71	13.75	155	296	451	17.5	65.6
Air Compressor	**92.8**	**2.12**	**2.50**	**18.76**	**27.80**	**143**	**753**	**896**	**48.2**	**84.0**
	92.1	2.34	2.69	16.97	23.96	143	546	689	41.2	79.2
	90.5	2.99	3.25	16.75	18.38	148	324	472	33.6	68.7
HRSG	**67.2**	**6.23**	**7.33**	**14.51**	**27.36**	**326**	**264**	**590**	**88.5**	**44.8**
	66.6	6.40	7.35	13.26	25.60	305	261	566	93.1	46.1
	67.6	6.10	6.65	11.71	23.51	257	284	541	100.7	52.5
Air Preheater	**84.6**	**2.63**	**3.09**	**14.51**	**20.81**	**137**	**189**	**326**	**43.4**	**57.9**
	84.7	3.15	3.62	13.26	18.94	150	206	365	42.9	57.8
	85.6	4.97	4.90	11.71	16.53	190	275	464	41.2	59.2

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

For the overall plant (First iteration): $C_{P,tot}$=$3355/h and $C_{L,tot}=C_7$=$157/h.

For the overall plant (Second iteration): $C_{P,tot}$=$2934/h and $C_{L,tot}=C_7$=$167/h.

Thermodynamic Data: Additional Iterations

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

$p_1 / p_2 = 9$ | $\eta_{AC} = 0.85$ | $\eta_{GT} = 0.85$ | $T_3 = 870\ K$ | $T_4 = 1520\ K$

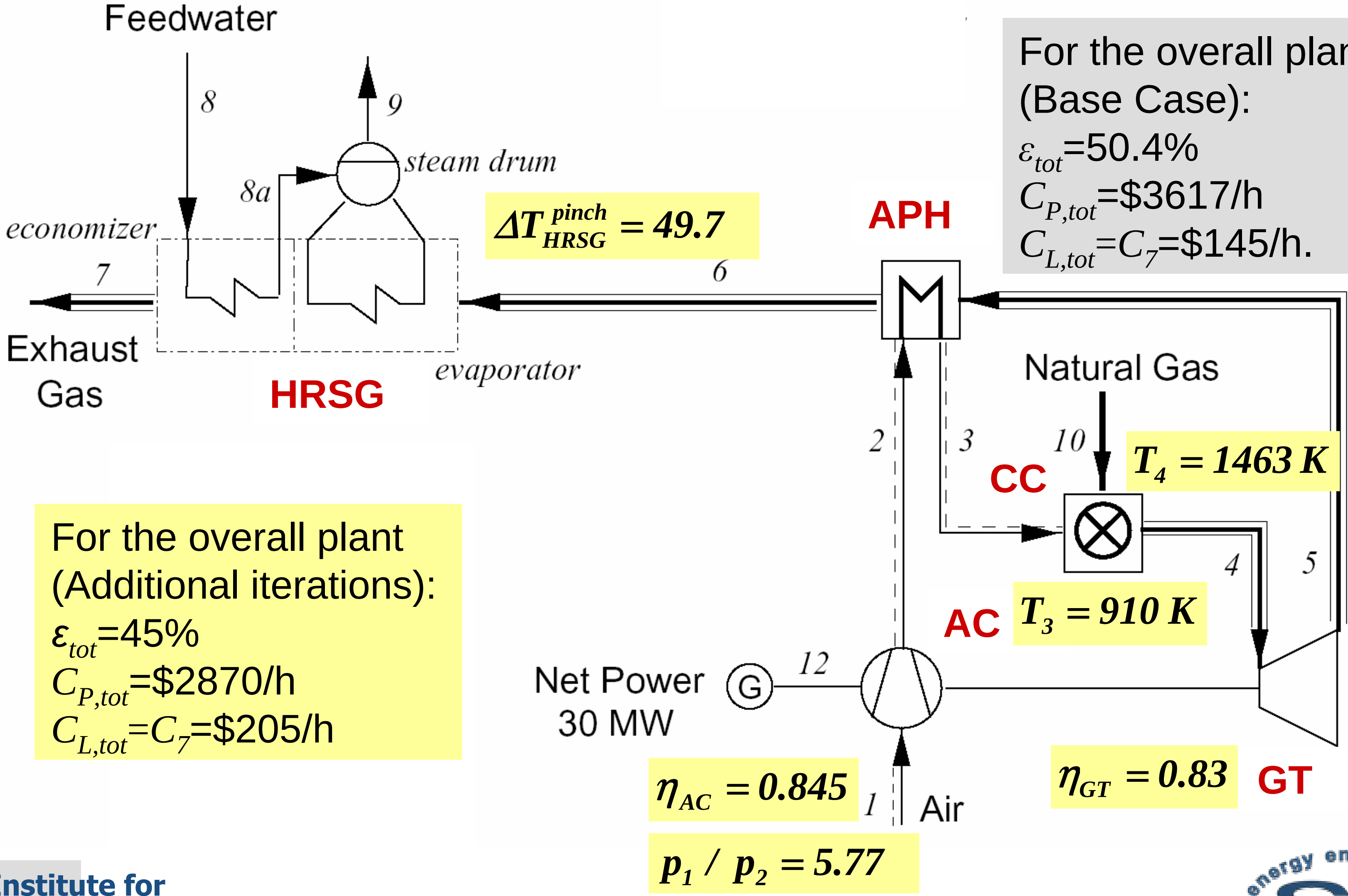
Second iteration

$p_1 / p_2 = 7$ | $\eta_{AC} = 0.83$ | $\eta_{GT} = 0.83$ | $T_3 = 910\ K$ | $T_4 = 1480\ K$

Additional iterations

$p_1 / p_2 = 5.77$ | $\eta_{AC} = 0.845$ | $\eta_{GT} = 0.83$ | $T_3 = 910\ K$ | $T_4 = 1463\ K$

Exergoeconomic Analysis: Additional Iterations



For the overall plant (Base Case):
ε_{tot}=50.4%
$C_{P,tot}$=\$3617/h
$C_{L,tot}=C_7$=\$145/h.

For the overall plant (Additional iterations):
ε_{tot}=45%
$C_{P,tot}$=\$2870/h
$C_{L,tot}=C_7$=\$205/h

Advanced Exergoeconomic Analysis

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

$$\dot{Z}_{k} = \dot{Z}_{k}^{UN} + \dot{Z}_{k}^{AV}$$

Splitting the exergy destruction and the investment cost into *unavoidable* and *avoidable* parts within the k-th component provides a realistic measure of the potential for improving the thermodynamic efficiency as well as of the economic effectiveness of a component.

Advanced Exergoeconomic Analysis

The exergy destruction rate that cannot be reduced due to technological limitations such as availability and cost of materials and manufacturing methods is the *unavoidable* (*UN*) part of the exergy destruction.

The *avoidable* (*AV*) part of the exergy destruction within a component can be avoided by improving the component.

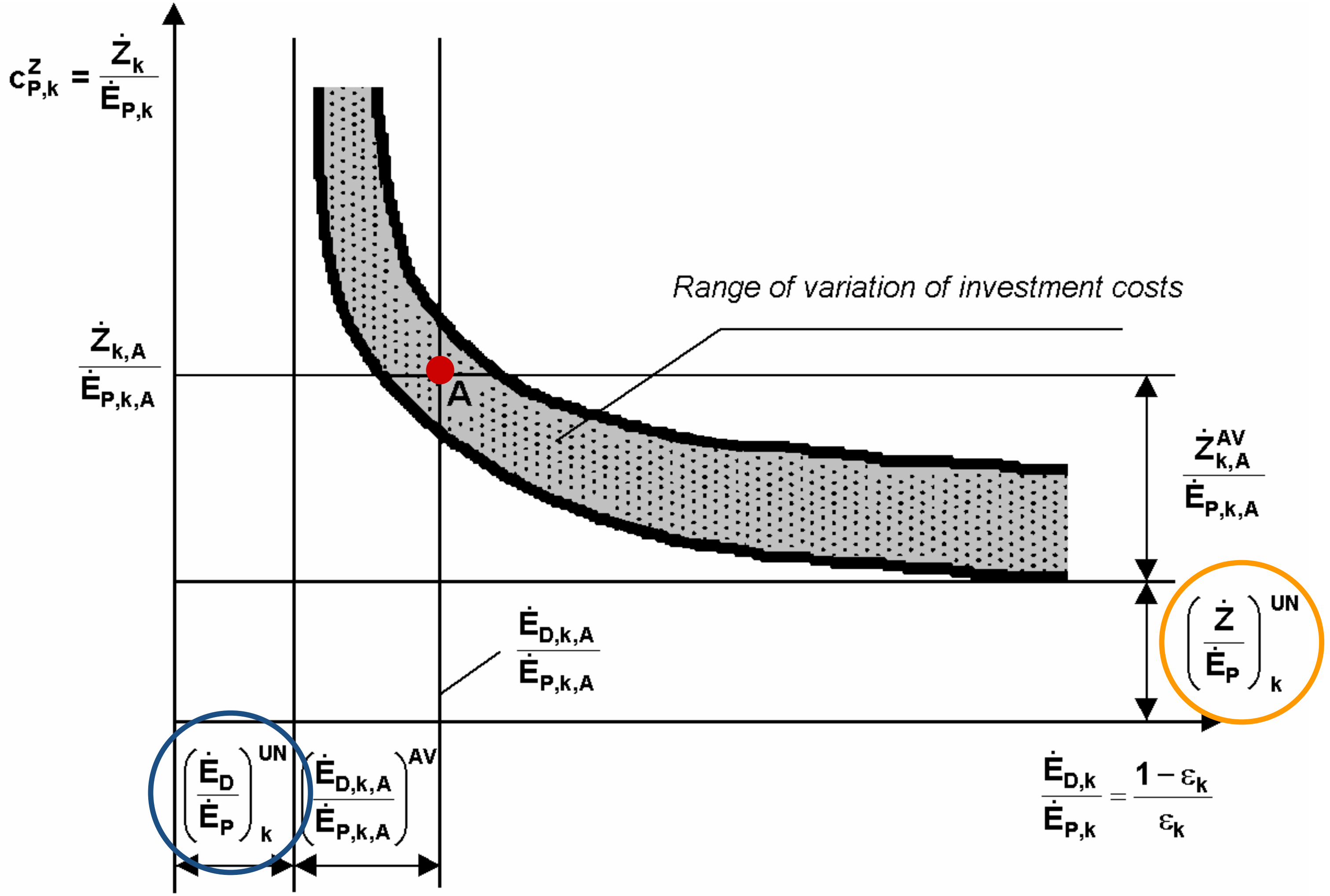
Advanced Exergoeconomic Analysis

The *unavoidable investment cost* ($\dot{Z}_k^{UN}$) for a component can be calculated by assuming an extremely inefficient version of this component.

To adjust for different component sizes, we calculate for each component the unavoidable cost per unit of exergy of the product $\left(\frac{\dot{Z}_k}{\dot{E}_P}\right)_k^{UN}$.

The avoidable investment cost is the difference between total investment cost and unavoidable investment cost for the component being considered: $\dot{Z}_{D,k}^{AV} = \dot{Z}_k - \dot{Z}_{D,k}^{UN}$.

Advanced Exergoeconomic Analysis



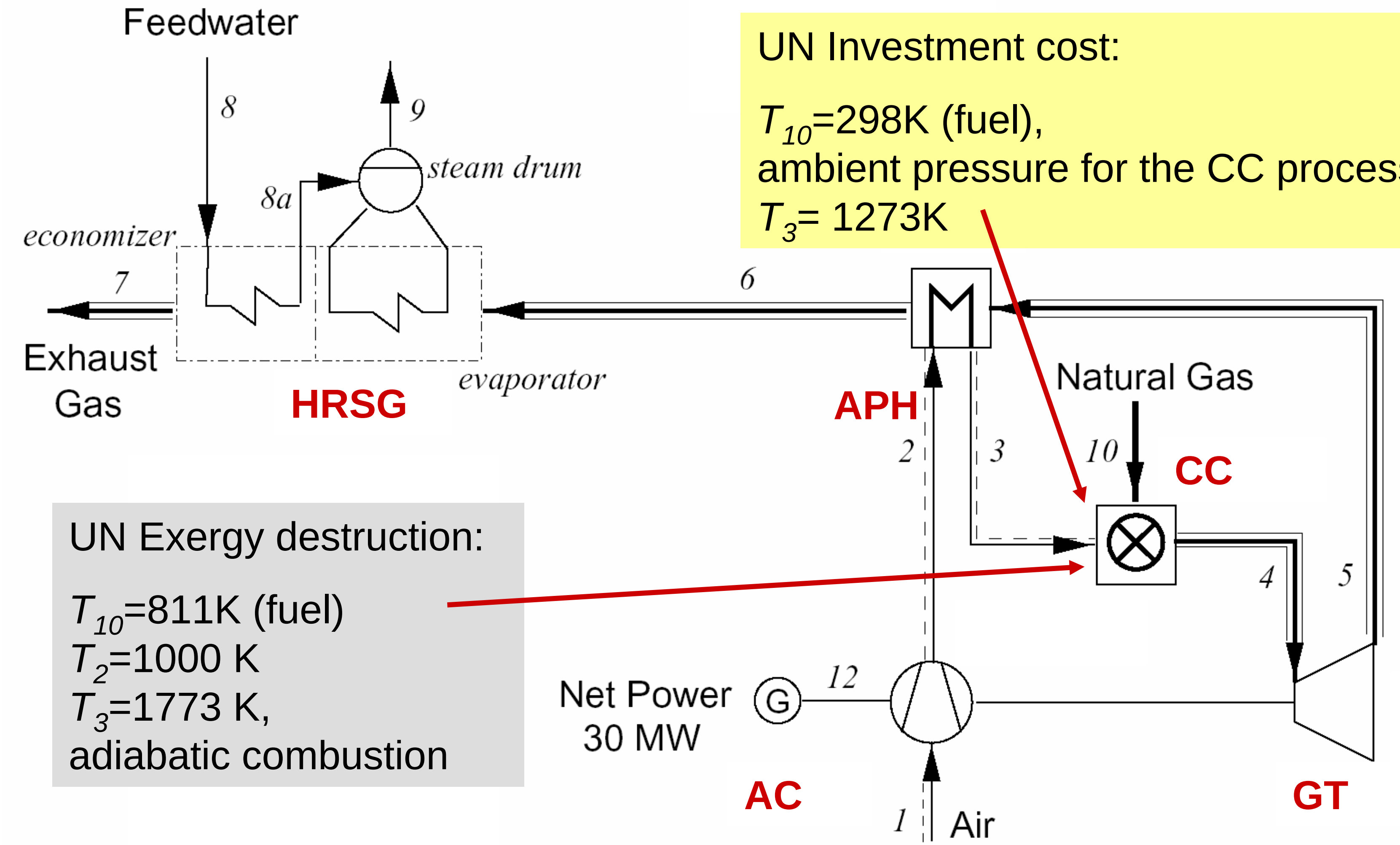
Thermodynamic Data

UN Investment cost:

T_{10}=298K (fuel),
ambient pressure for the CC process
T_3= 1273K

UN Exergy destruction:

T_{10}=811K (fuel)
T_2=1000 K
T_3=1773 K,
adiabatic combustion



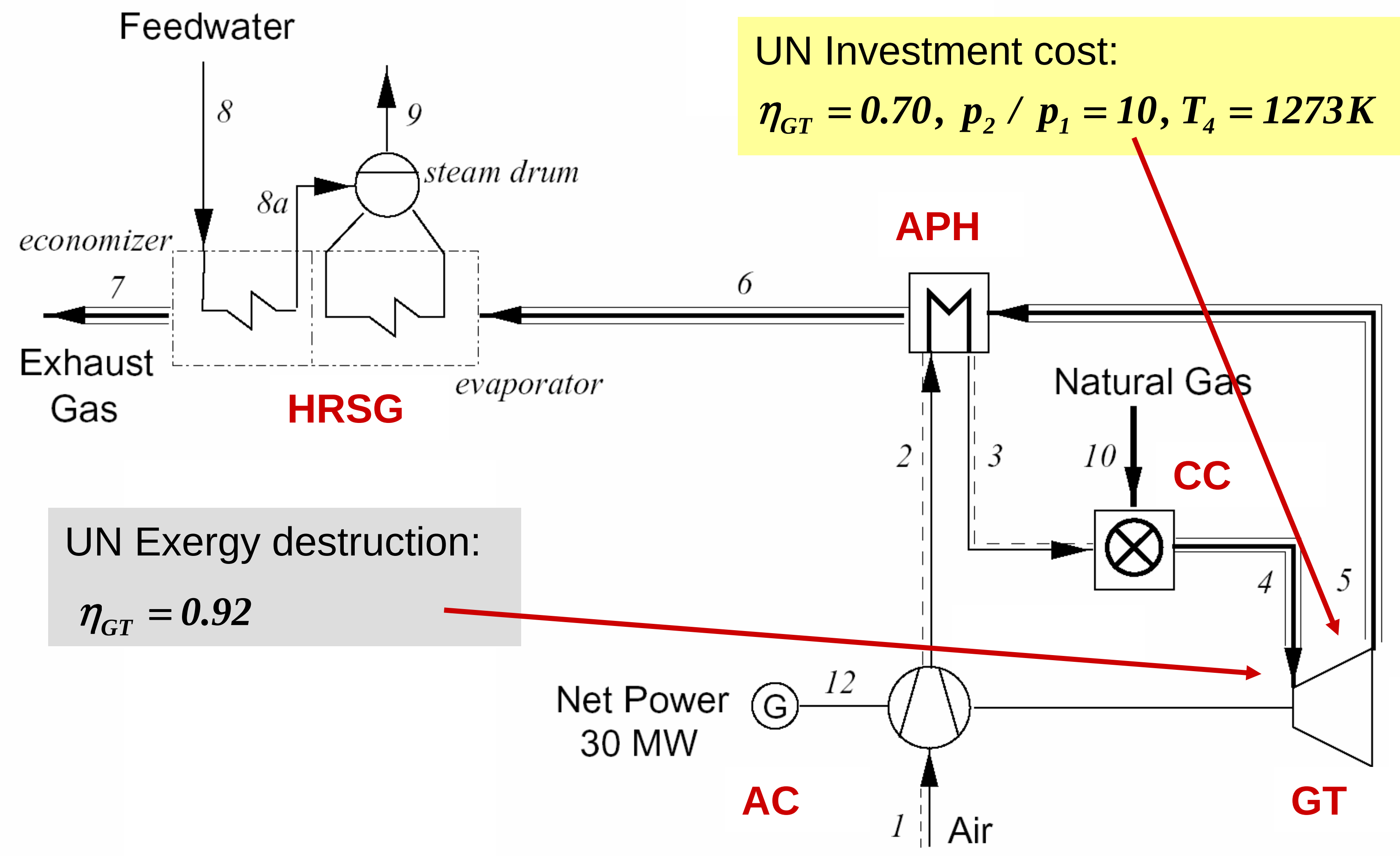
Thermodynamic Data

UN Investment cost:

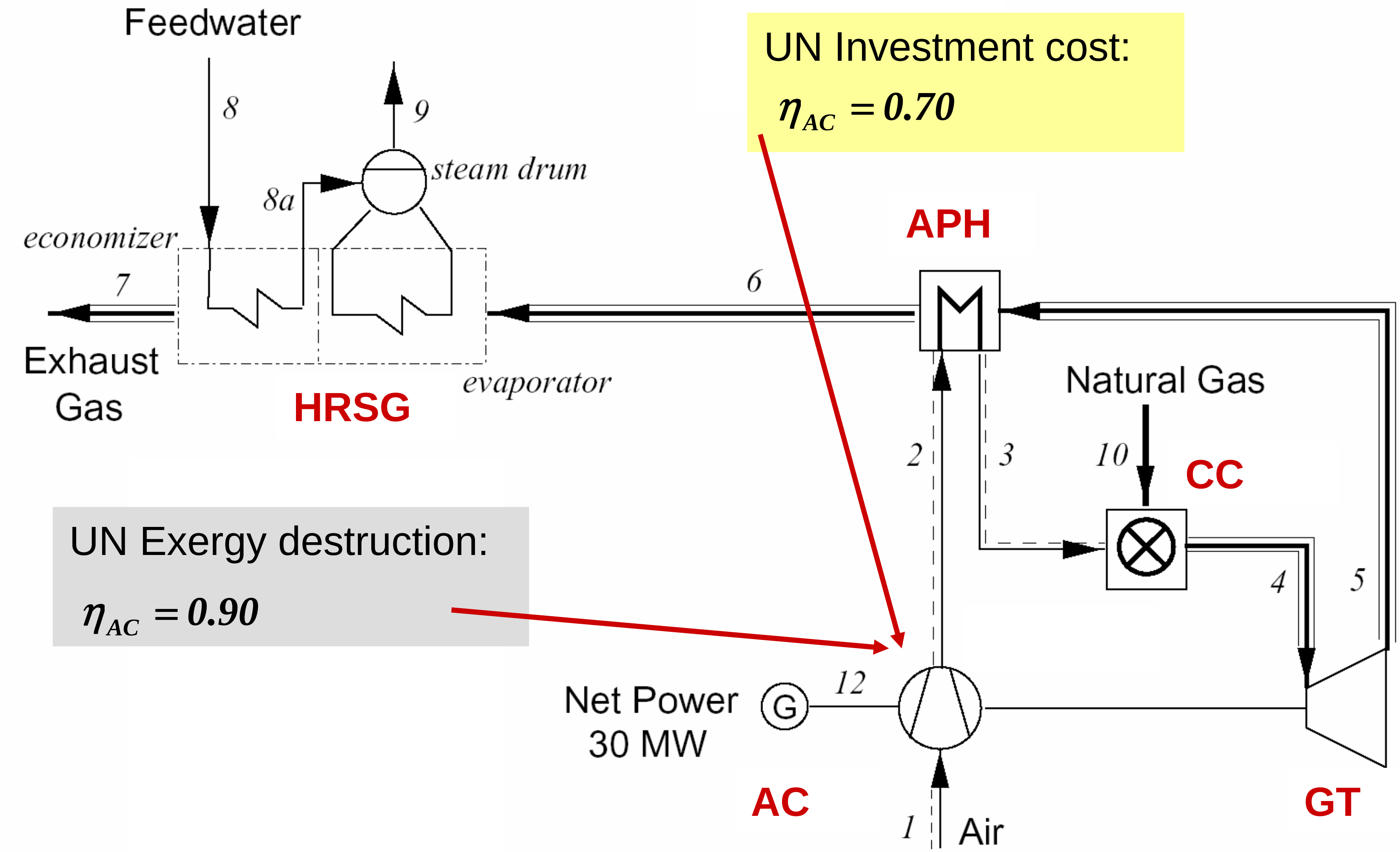
$\eta_{GT} = 0.70, \; p_2 / p_1 = 10, \; T_4 = 1273 K$

UN Exergy destruction:

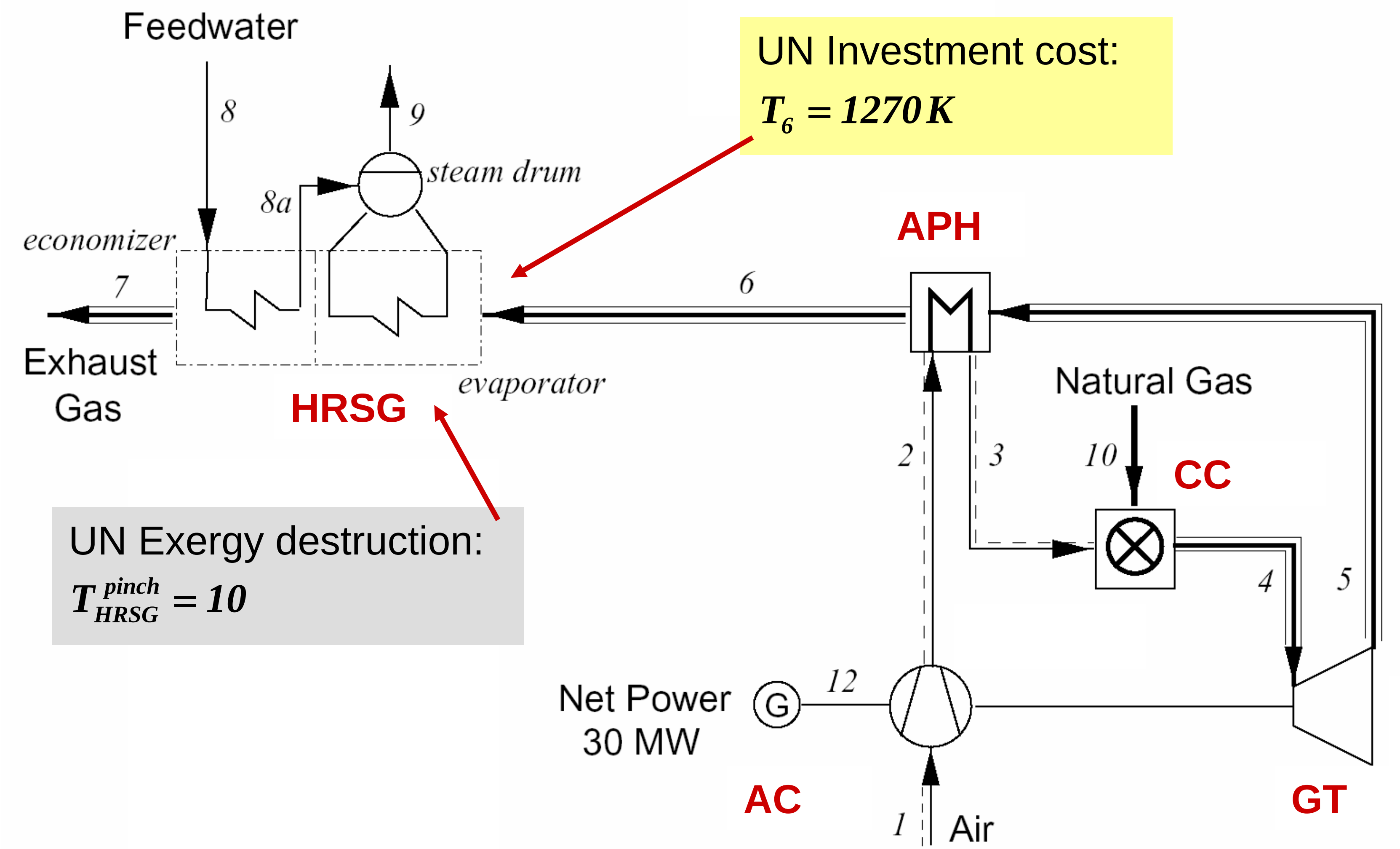
$\eta_{GT} = 0.92$



Thermodynamic Data



Thermodynamic Data



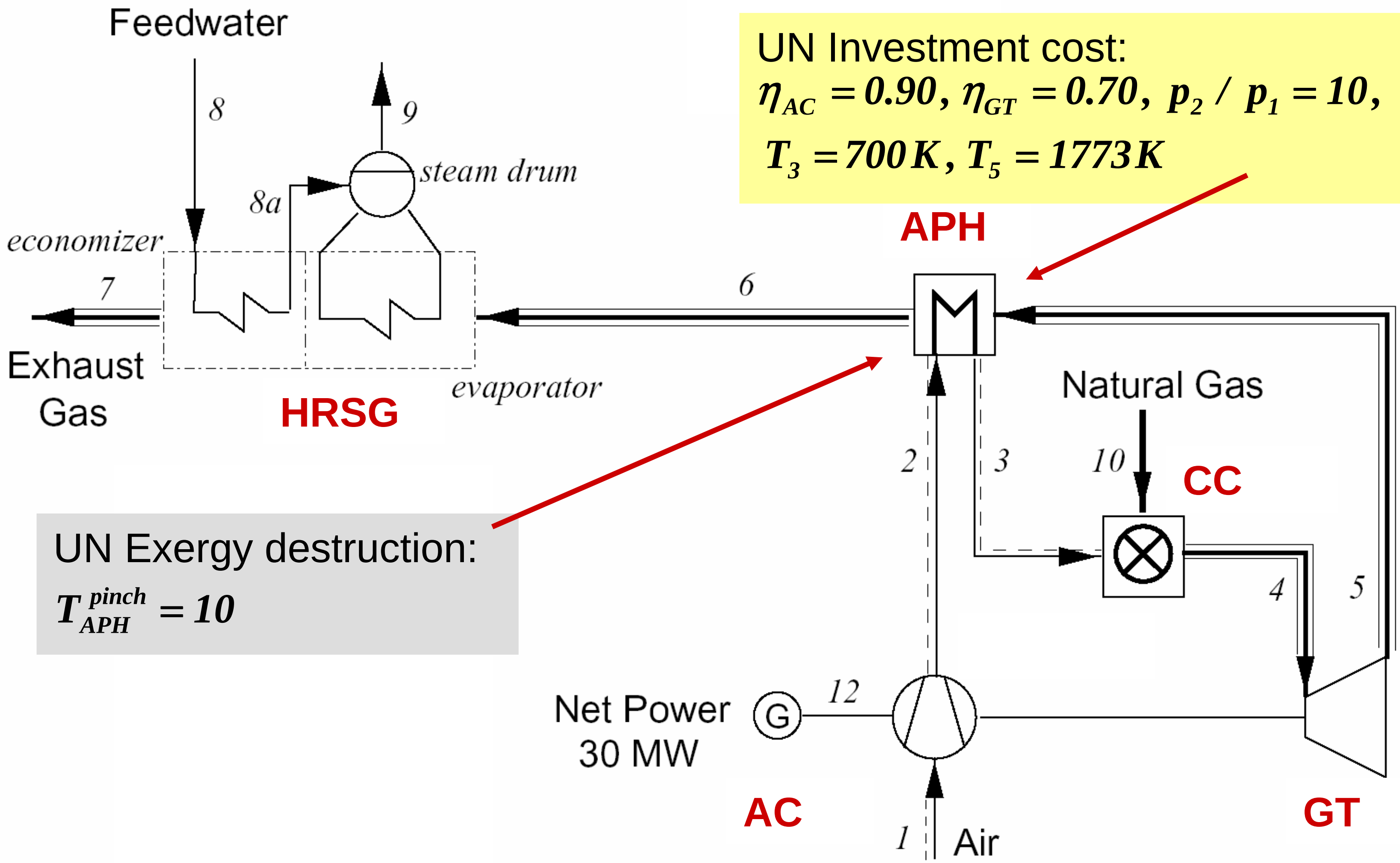
UN Investment cost:

$T_6 = 1270\,K$

UN Exergy destruction:

$T_{HRSG}^{pinch} = 10$

Thermodynamic Data



UN Investment cost:

$\eta_{AC} = 0.90, \eta_{GT} = 0.70, \; p_2 / p_1 = 10,$

$T_3 = 700\,K, T_5 = 1773\,K$

UN Exergy destruction:

$T_{APH}^{pinch} = 10$

Advanced Exergoeconomic Analysis

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

Advanced Exergoeconomic Analysis

Component	$\dot{Z}_k + \dot{C}_{D,k}$	$\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV}$	$\frac{\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV}}{\dot{Z}_k + \dot{C}_{D,k}}$	$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}}$	$f_k^* = \frac{\dot{Z}_k^{AV}}{\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV}}$
	[$/h]	[$/h]	[%]	[%]	[%]
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