Technische Universität Berlin
Institute for Energy Engineering

Thermoeconomic Analysis

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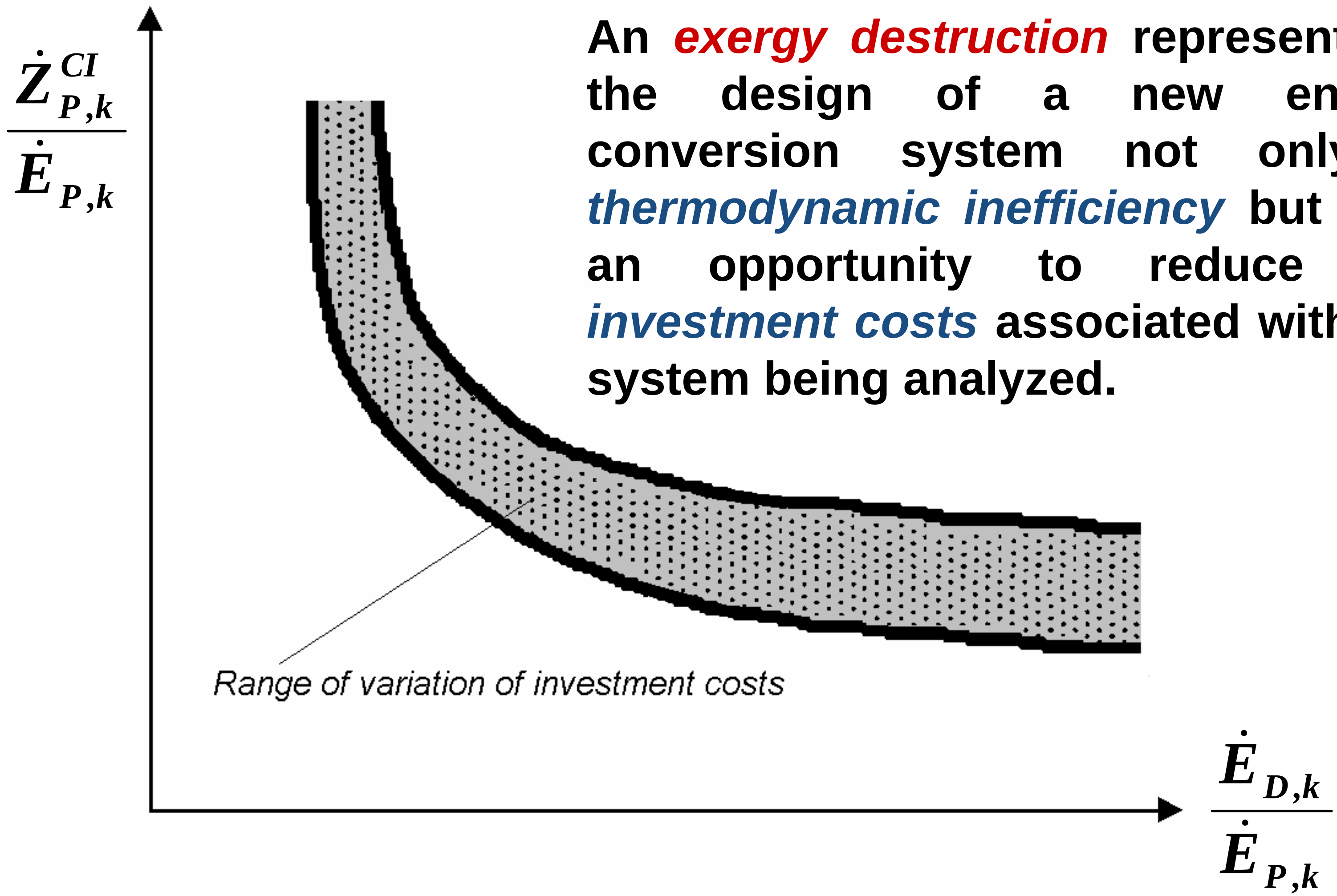
Definition

Thermoeconomics (= Exergoeconomics) is a unique combination of exergy analysis and cost analysis to provide the designer or operator of an energy conversion system with information crucial to the design of a cost-effective system. This information cannot be supplied through energy, exergy, and cost analyses conducted separately.

Exergoeconomics is an exergy-aided cost reduction approach that uses the exergy costing principle.

Thermodynamics and Economics - 1

An *exergy destruction* represents in the design of a new energy conversion system not only a *thermodynamic inefficiency* but also an opportunity to reduce the *investment costs* associated with the system being analyzed.



Thermodynamics and Economics - 2

Exergy is the only rational basis for assigning *monetary values* to the interactions that an energy conversion system experiences with its surroundings and to the sources of *thermodynamic inefficiencies* within it.

***The exergy costing principle* forms the basis for calculating the costs associated with each material and each energy stream in an energy conversion system.**

Exergy costing

$$\dot{C}_j = c_j \dot{E}_j = c_j e_j \dot{m}_j$$

$\dot{C}_j$ cost stream; $\dot{E}_j$ exergy stream; $\dot{m}_j$ mass flow rate;

c_j average cost per unit of exergy

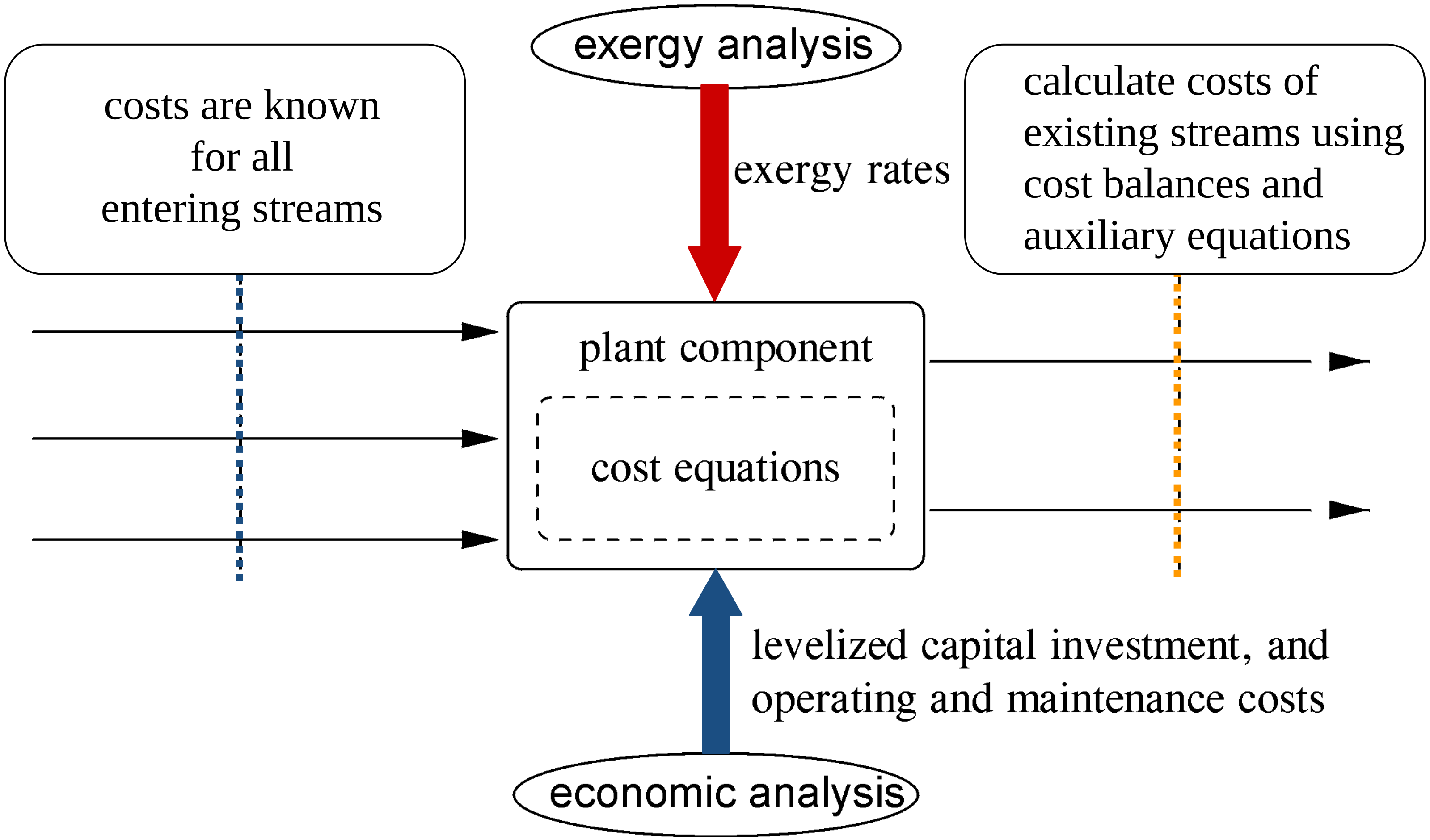
Cost Sources

The real cost sources in an energy conversion system are:

- **capital investment for each component**
- **operating and maintenance expenses**
- **cost of exergy destruction within each component**
- **cost of exergy loss from the overall system**

$$E_{P,tot} = const \quad \text{or} \quad E_{F,tot} = const$$

Exergy Costing



Exergy Costing

Costs of exergy transfer associated with heat and work

$$\dot{C}_Q = c_Q \cdot \dot{E}_Q$$

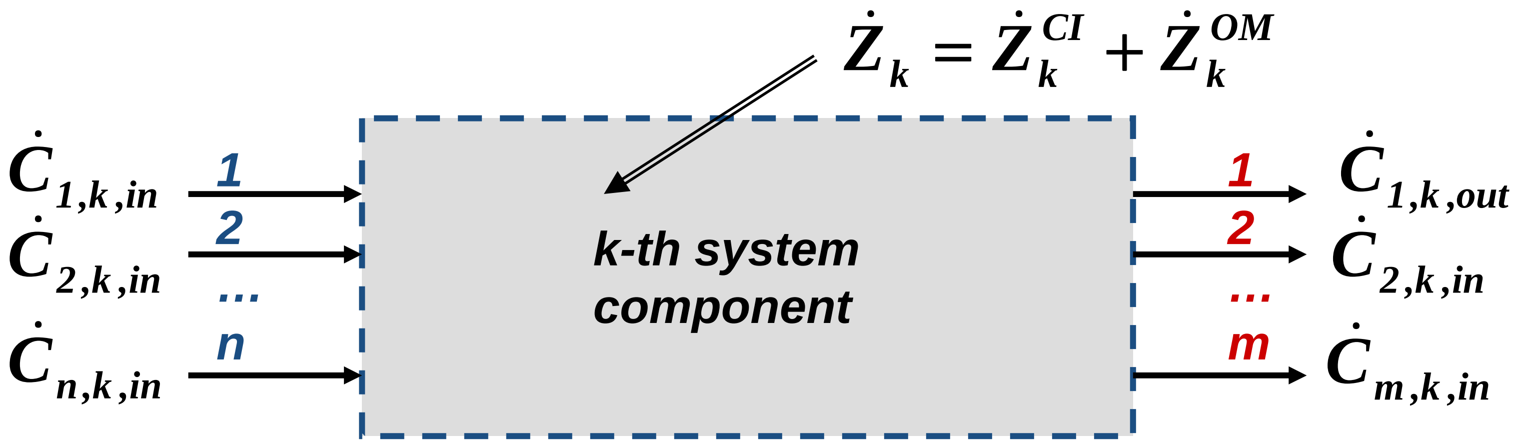
$$\dot{C}_W = c_W \cdot \dot{W}$$

c_j, c_Q, and c_W **denote average costs per unit of exergy (for example, €/J, €/GJ).**

$$\dot{C}_j = c_j \dot{E}_j = c_j^{PH} \dot{E}_j^{PH} + c_j^{CH} \dot{E}_j^{CH} =$$

$$= \dot{m}_j \left(c_j^{PH} e_j^{PH} + c_j^{CH} e_j^{CH} \right) = \dot{m}_j \left(c_j^{T} e_j^{T} + c_j^{M} e_j^{M} + c_j^{CH} e_j^{CH} \right)$$

Cost Balance



Cost balance applied to the *k*-th system component

$$\sum_{j=1}^{n} \dot{C}_{j,k,in} + \left(\dot{Z}_k^{CI} + \dot{Z}_k^{OM}\right) = \sum_{j=1}^{m} \dot{C}_{j,k,out}$$

$$\sum_{j=1}^{n} \left(c_j \dot{E}_j\right)_{k,in} + \dot{Z}_k = \sum_{j=1}^{m} \left(c_j \dot{E}_j\right)_{k,out}$$

Cost of Product and Fuel

A *fuel* and a *product* are defined for each component of a system.

The cost flow rates associated with the fuel $\dot{C}_{F,k}$ and product $\dot{C}_{P,k}$ of a component are calculated in a similar way to the exergy flow rates $\dot{E}_{F,k}$ and $\dot{E}_{P,k}$.

Cost balances

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k$$

$$\dot{C}_{P,tot} = \dot{C}_{F,tot} + \dot{Z}_{tot} - \dot{C}_{L,tot}$$

Cost of the Exergy Destruction

Cost balances

$$c_{P,k}\dot{E}_{P,k} = c_{F,k}\dot{E}_{F,k} + \dot{Z}_k$$

$$c_{P,tot}\dot{E}_{P,tot} = c_{F,tot}\dot{E}_{F,tot} + \dot{Z}_{tot} + \dot{C}_{L,tot}$$

Average cost of fuel and product for the *k*-th component

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \qquad c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}}$$

Average cost of fuel and product for the overall system

$$c_{F,tot} = \frac{\dot{C}_{F,tot}}{\dot{E}_{F,tot}} \qquad c_{P,tot} = \frac{\dot{C}_{P,tot}}{\dot{E}_{P,tot}}$$

Thermoeconomic Variables

Cost rate associated with *exergy destruction* within the *k*-th component

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

The cost per unit of exergy destruction is different for each component and depends on the relative position of the component within the energy conversion system

$$\dot{C}_{D,tot} = c_{F,tot}\dot{E}_{D,tot}$$

Thermoeconomic Variables

Relative cost difference **between the average cost per exergy unit of product and average cost per exergy unit of fuel**

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} = \frac{c_{F,k}\dot{E}_{D,k} + \dot{Z}_k}{c_{F,k}\dot{E}_{P,k}}$$

$$= \frac{1 - \varepsilon_k}{\varepsilon_k} + \frac{\dot{Z}_k}{c_{F,k}\dot{E}_{P,k}}$$

Exergoeconomic factor

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}\dot{E}_{D,k}}$$

Auxiliary Costing Equations

F Equations

Total cost associated with the removal of exergy from an exergy stream in a component

=

Cost at which the removed exergy was supplied to the same stream in upstream components

The exergy difference of this stream between inlet and outlet is considered in the definition of *fuel* for the component.

Auxiliary Costing Equations

P Equations

Each exergy unit is supplied to any stream associated with the product of a component at the same average cost $c_{P,k}$

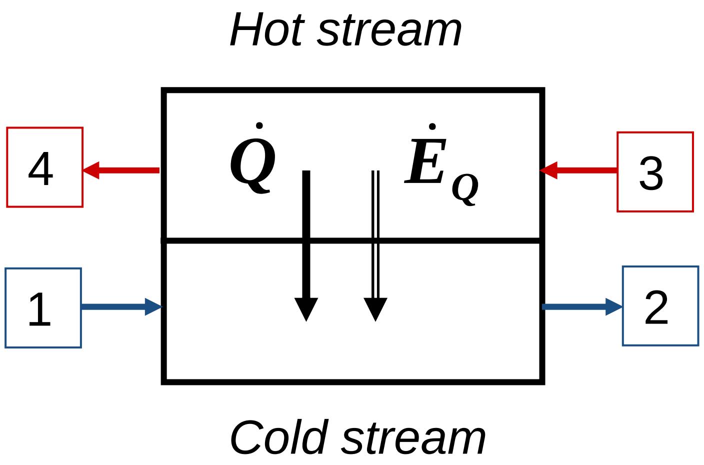
This cost can be calculated directly from the cost balance and the *F* equations.

Real Processes

All real processes are *irreversible* due to effects such as:

- **heat transfer through a finite temperature difference,**
- **mixing of matter at different compositions or states,**
- **unrestrained expansion,**
- **friction, and**
- **chemical reaction.**

Heat Transfer - 1

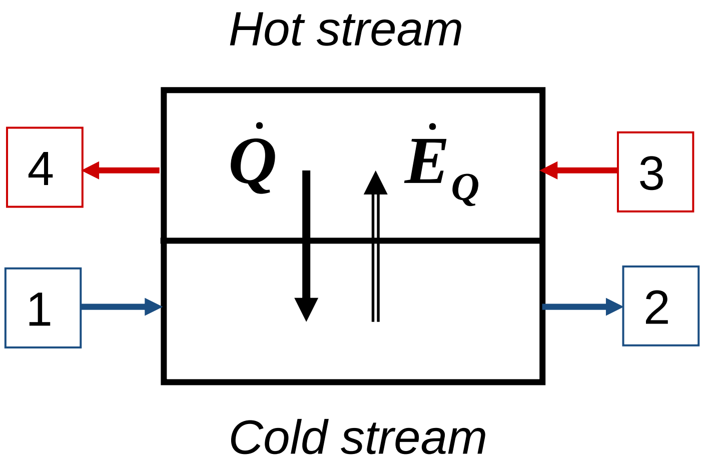


$$T_1 > T_0$$

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

$$\frac{\dot{C}_4}{\dot{E}_4} = \frac{\dot{C}_3}{\dot{E}_3}$$

Heat Transfer - 2

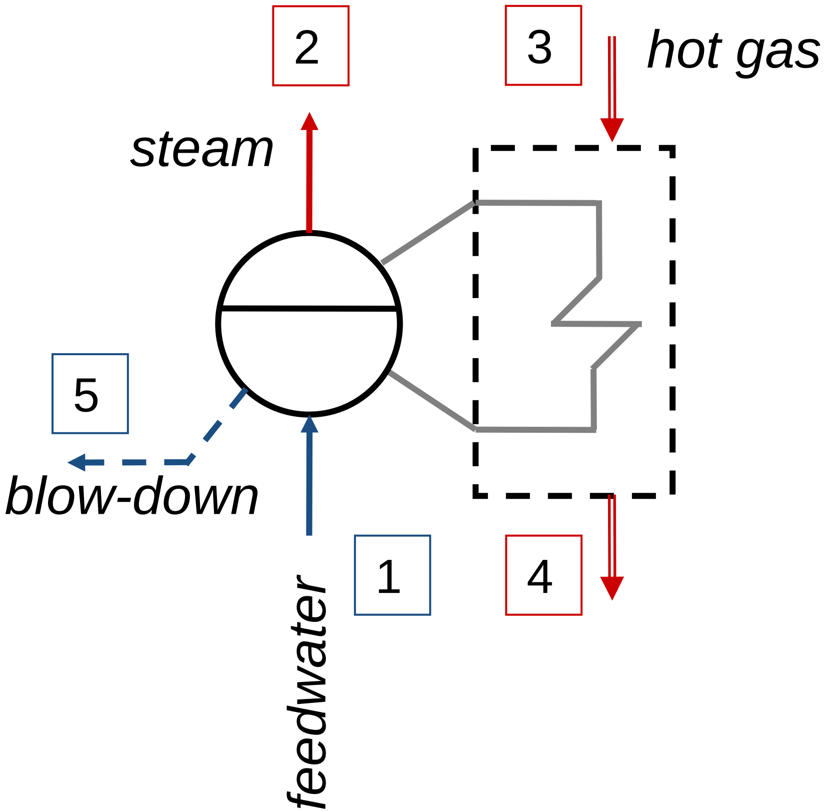


$$T_3 < T_0$$

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

$$\frac{\dot{C}_1}{\dot{E}_1} = \frac{\dot{C}_2}{\dot{E}_2}$$

Heat Transfer - 3

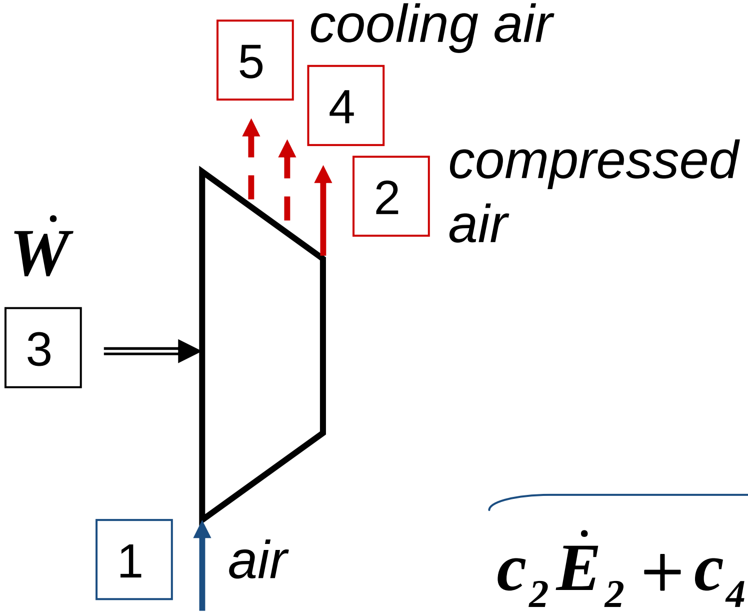


Evaporator including steam drum

$$\overbrace{\dot{C}_2 + \dot{C}_5 - \dot{C}_1}^{\dot{C}_P} = \dot{Z}_{EV} + \overbrace{\dot{C}_3 - \dot{C}_4}^{\dot{C}_F}$$

$$\frac{c_5 e_5 - c_1 e_1}{e_5 - e_1} = \frac{c_2 e_2 - c_1 e_1}{e_2 - e_1}$$

Compressor, Pump, or Fan



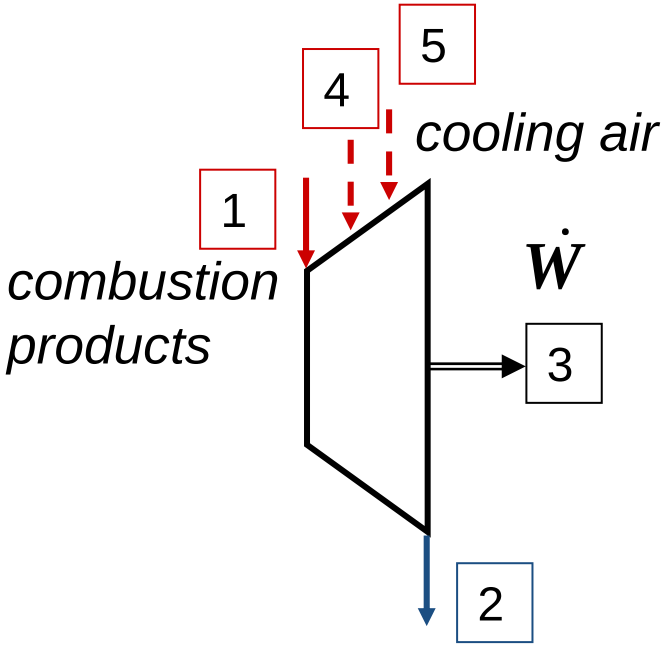
Compressor with cooling air extractions

$$\overbrace{c_2\dot{E}_2 + c_4\dot{E}_4 + c_5\dot{E}_5 - c_1\dot{E}_1}^{\dot{C}_P} = \dot{Z}_{CM} + \overbrace{c_3\dot{E}_3}^{\dot{C}_F}$$

$$\frac{c_2e_2 - c_1e_1}{e_2 - e_1} = \frac{c_4e_4 - c_1e_1}{e_4 - e_1} = \frac{c_5e_5 - c_1e_1}{e_5 - e_1}$$

Turbine or Expander

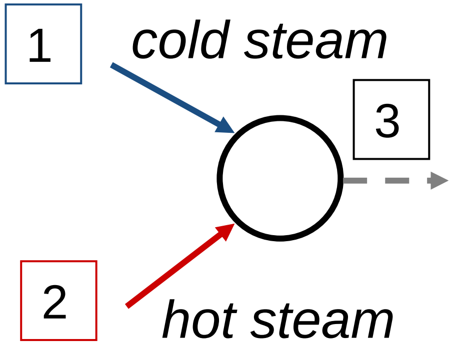
Expander with cooling air supply

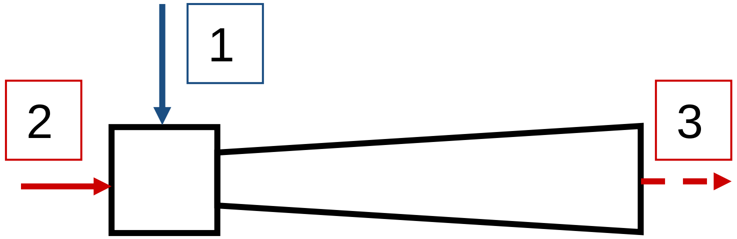


$$\underbrace{\dot{C}_3}_{\dot{C}_P} = \dot{Z}_{EX} + \underbrace{\left(\dot{C}_1 + \dot{C}_4 + \dot{C}_5 - \dot{C}_2\right)}_{\dot{C}_F}$$

$$\frac{\dot{C}_2}{\dot{E}_2} = \frac{\dot{C}_1 + \dot{C}_4 + \dot{C}_5}{\dot{E}_1 + \dot{E}_4 + \dot{E}_5}$$

Mixing Unit and Ejector

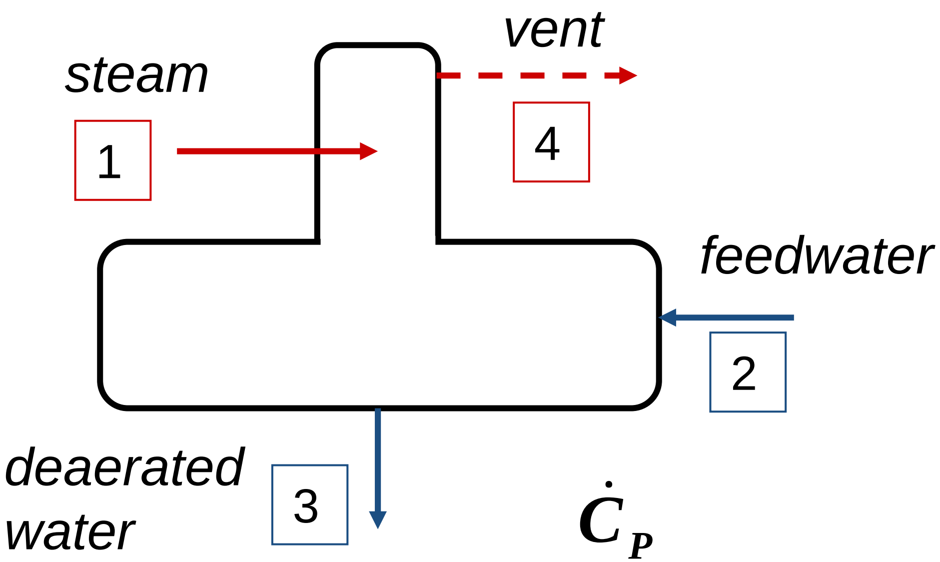




$$\overbrace{\dot{m}_1\left(c_{3,1}e_3 - c_1 e_1\right)}^{\dot{C}_P} = \dot{Z}_M + \overbrace{\dot{m}_2 c_2\left(e_2 - e_3\right)}^{\dot{C}_F}$$

$$c_{3,1} = c_3 + \frac{\dot{m}_2}{\dot{m}_1}\left(c_3 - c_2\right)$$

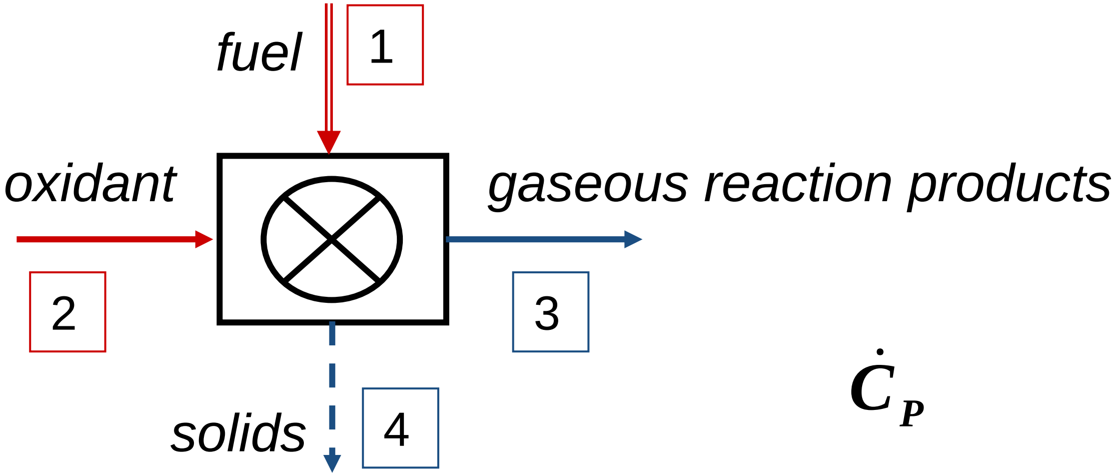
Deaerator



$$\overbrace{\dot{m}_2\left(e_3c_3 - e_2c_2\right)}^{\dot{C}_P} = \dot{Z}_{DA} + \overbrace{\left(\dot{m}_1 - \dot{m}_4\right)\left(e_1c_1 - e_3c_3\right) +}^{\dot{C}_F}$$
$$\dot{m}_4\left(e_1c_1 - e_4c_4\right)$$

$$\frac{\dot{C}_4}{\dot{E}_4} = \frac{\dot{C}_1}{\dot{E}_1} = \frac{\dot{C}_{3,1}}{\dot{E}_{3,1}}$$

Combustion Chamber

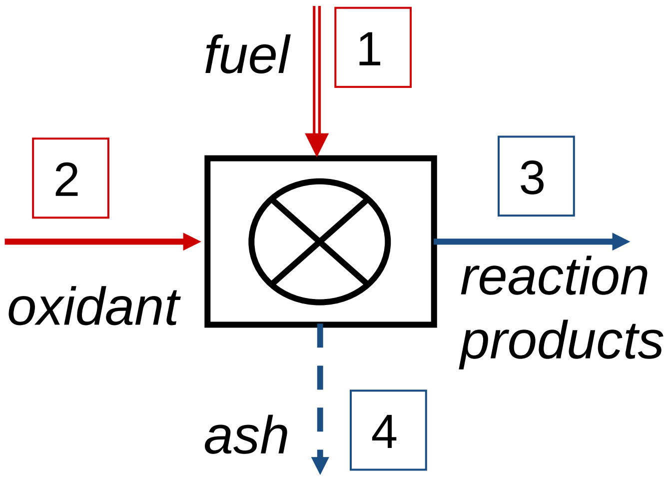


$$\underbrace{\left(\dot{C}_3 - \dot{C}_2\right)}_{\dot{C}_P} = \dot{Z}_{CC} + \underbrace{\left(\dot{C}_1 - \dot{C}_4\right)}_{\dot{C}_F}$$

$$\frac{\dot{C}_4}{\dot{E}_4} = \frac{\dot{C}_1}{\dot{E}_1}$$

Gasifier

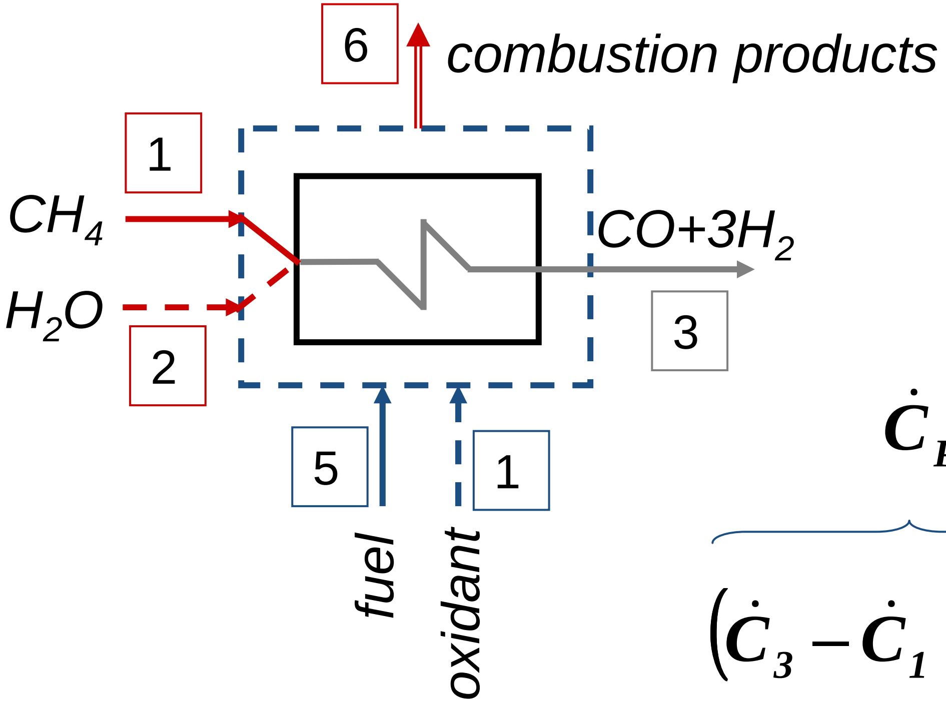
$$\overbrace{\dot{C}_3^{CH} + \left(\dot{C}_3^{PH} + \dot{C}_4^{PH} - \dot{C}_1^{PH} - \dot{C}_2^{PH}\right)}^{\dot{C}_P} = \dot{Z}_{GS} + \overbrace{\left(\dot{C}_1^{CH} + \dot{C}_2^{CH} - \dot{C}_4^{CH}\right)}^{\dot{C}_F}$$



$$\frac{\dot{C}_3^{CH}}{\dot{E}_3^{CH}} = \frac{\dot{C}_3^{PH} + \dot{C}_4^{PH} - \dot{C}_1^{PH} - \dot{C}_2^{PH}}{\dot{E}_3^{PH} + \dot{E}_4^{PH} - \dot{E}_1^{PH} - \dot{E}_2^{PH}}$$

$$\frac{\dot{C}_4^{CH}}{\dot{E}_4^{CH}} = \frac{\dot{C}_1^{CH}}{\dot{E}_1^{CH}}$$

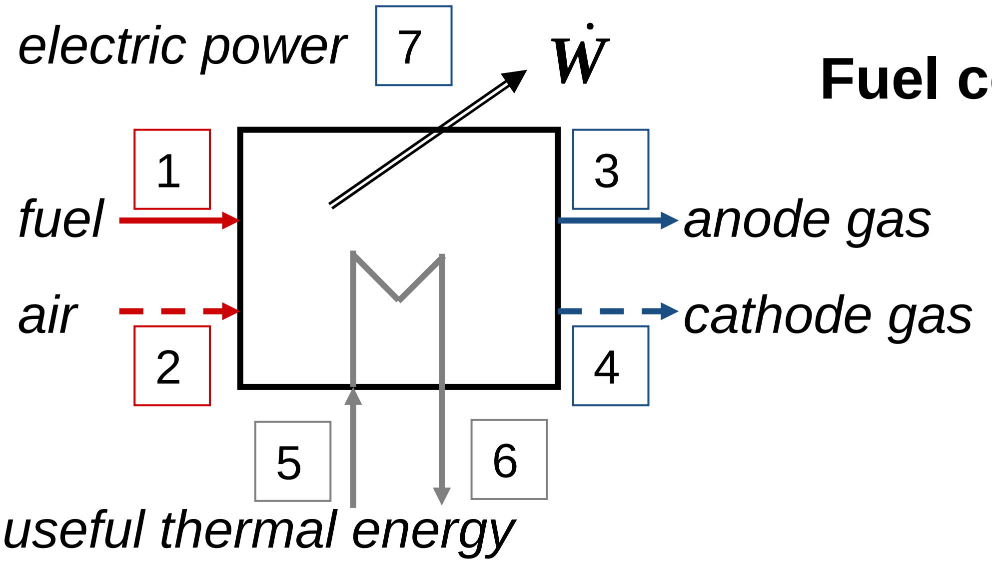
Steam Reformer



$$\underbrace{\left(\dot{C}_3 - \dot{C}_1 - \dot{C}_2\right)}_{\dot{C}_P} = \dot{Z}_{SR} + \underbrace{\left(\dot{C}_4 + \dot{C}_5 - \dot{C}_6\right)}_{\dot{C}_F}$$

$$\frac{\dot{C}_6}{\dot{E}_6} = \frac{\dot{C}_4 + \dot{C}_5}{\dot{E}_4 + \dot{E}_5}$$

Fuel Cell - 1



Fuel cell as part of a system

$$\overbrace{\dot{C}_7 + \left(\dot{C}_6 - \dot{C}_5\right) + \left(\dot{C}_3^{PH} - \dot{C}_1^{PH}\right) + \left(\dot{C}_4^{PH} - \dot{C}_2^{PH}\right)}^{\dot{C}_P} =$$

$$\dot{Z}_{FC} + \underbrace{\left(\dot{C}_1^{CH} + \dot{C}_2^{CH}\right) - \left(\dot{C}_3^{CH} + \dot{C}_4^{CH}\right)}_{\dot{C}_F}$$

Fuel Cell - 1

Fuel cell as part of a system

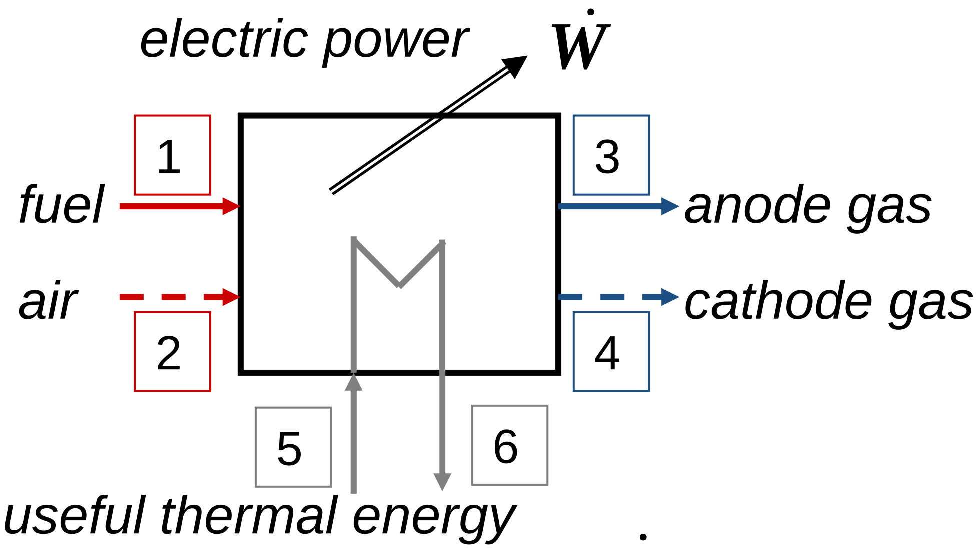
$$\dot{C}_P \left\{ \dot{C}_7 + \left(\dot{C}_6 - \dot{C}_5\right) + \left(\dot{C}_3^{PH} - \dot{C}_1^{PH}\right) + \left(\dot{C}_4^{PH} - \dot{C}_2^{PH}\right) = \right.$$

$$\dot{Z}_{FC} + \underbrace{\left(\dot{C}_1^{CH} + \dot{C}_2^{CH}\right) - \left(\dot{C}_3^{CH} + \dot{C}_4^{CH}\right)}_{\dot{C}_F}$$

$$\frac{\dot{C}_3^{CH}}{\dot{E}_3^{CH}} = \frac{\dot{C}_1^{CH}}{\dot{E}_1^{CH}} \qquad \frac{\dot{C}_4^{CH}}{\dot{E}_4^{CH}} = \frac{\dot{C}_2^{CH}}{\dot{E}_2^{CH}}$$

$$\frac{\dot{C}_3^{PH} - \dot{C}_1^{PH}}{\dot{E}_3^{PH} - \dot{E}_1^{PH}} = \frac{\dot{C}_4^{PH} - \dot{C}_2^{PH}}{\dot{E}_4^{PH} - \dot{E}_2^{PH}} = \frac{\dot{C}_6 - \dot{C}_5}{\dot{E}_6 - \dot{E}_5} = \frac{\dot{C}_7}{\dot{E}_7}$$

Fuel Cell - 2

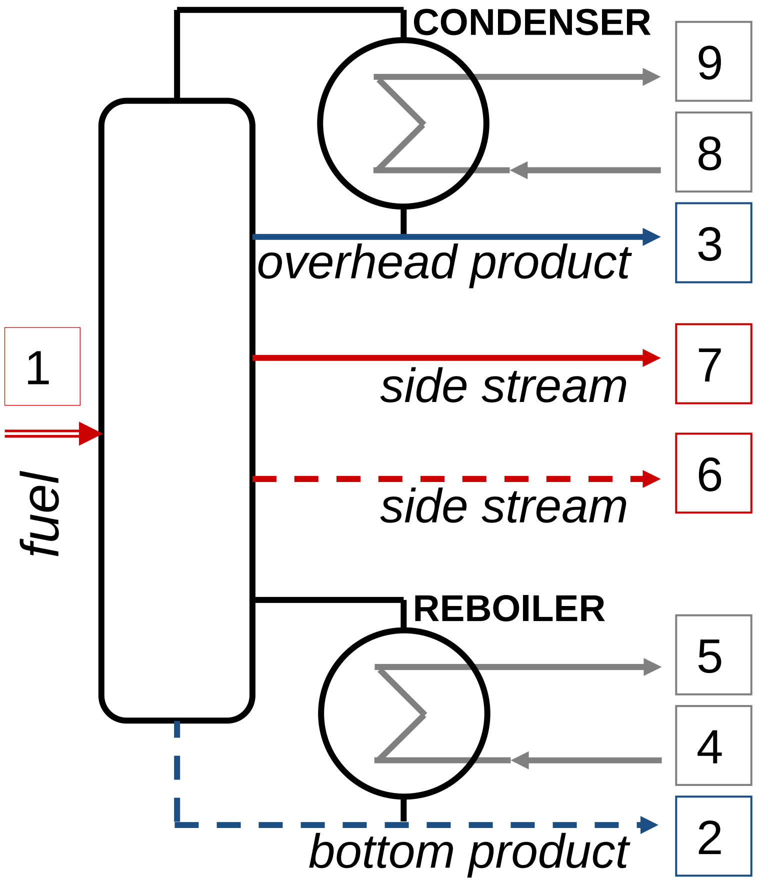


Stand-alone fuel cell

$$\underbrace{\dot{C}_7 + \left(\dot{C}_6 - \dot{C}_5\right)}_{\dot{C}_P} = \dot{Z}_{FC} + \underbrace{\left(\dot{C}_1 + \dot{C}_2\right)}_{\dot{C}_F} - \underbrace{\left(\dot{C}_3 + \dot{C}_4\right)}_{\dot{C}_L}$$

$$\frac{\dot{C}_3}{\dot{E}_3} = \frac{\dot{C}_1}{\dot{E}_1} \qquad \frac{\dot{C}_4}{\dot{E}_4} = \frac{\dot{C}_2}{\dot{E}_2} \qquad \frac{\dot{C}_6 - \dot{C}_5}{\dot{E}_6 - \dot{E}_5} = \frac{\dot{C}_7}{\dot{E}_7}$$

Distillation Column



$$\dot{C}_P \left\{ \begin{aligned} & c_2^{CH}\dot{E}_2^{CH} + c_3^{CH}\dot{E}_3^{CH} + \\ & c_6^{CH}\dot{E}_6^{CH} + c_7^{CH}\dot{E}_7^{CH} - c_1^{CH}\dot{E}_1^{CH} + \\ & \dot{m}_6\left(c_6^{PH}e_6^{PH} - c_1^{PH}e_1^{PH}\right) + \\ & \dot{m}_2\left(c_2^{PH}e_2^{PH} - c_1^{PH}e_1^{PH}\right) + \\ & \left(c_9\dot{E}_9 - c_8\dot{E}_8\right) \qquad = \end{aligned} \right.$$

$$\dot{Z}_{DC} +$$

$$\dot{C}_F \left\{ \begin{aligned} & \left(c_4\dot{E}_4 - c_5\dot{E}_5\right) + \\ & \dot{m}_7\left(c_1^{PH}e_1^{PH} - c_7^{PH}e_7^{PH}\right) + \\ & \dot{m}_3\left(c_1^{PH}e_1^{PH} - c_3^{PH}e_3^{PH}\right) \end{aligned} \right.$$

Distillation Column

F **Equations:** $c_5 = c_4$ $\quad c_7^{PH} = c_3^{PH} = c_1^{PH}$

P **Equations:**

$$\frac{\dot{m}_6\left(c_6^{PH}e_6^{PH} - c_1^{PH}e_1^{PH}\right)}{\dot{m}_6\left(e_6^{PH} - e_1^{PH}\right)} = \frac{\dot{m}_2\left(c_2^{PH}e_2^{PH} - c_1^{PH}e_1^{PH}\right)}{\dot{m}_2\left(e_2^{PH} - e_1^{PH}\right)}$$

$$= \frac{\dot{m}_2\left(c_2^{CH}e_2^{CH} - c_1^{CH}e_1^{CH}\right)}{\dot{m}_2\left(e_2^{CH} - e_1^{CH}\right)} = \frac{\dot{m}_3\left(c_3^{CH}e_3^{CH} - c_1^{CH}e_1^{CH}\right)}{\dot{m}_3\left(e_3^{CH} - e_1^{CH}\right)}$$

$$= \frac{\dot{m}_6\left(c_6^{CH}e_6^{CH} - c_1^{CH}e_1^{CH}\right)}{\dot{m}_6\left(e_6^{CH} - e_1^{CH}\right)} = \frac{\dot{m}_7\left(c_7^{CH}e_7^{CH} - c_1^{CH}e_1^{CH}\right)}{\dot{m}_7\left(e_7^{CH} - e_1^{CH}\right)}$$

The exergy increase of the cooling water (stream 8) is an exergy loss $c_9 = 0$

Application of Exergoeconomics

- **Design Analysis and Optimization**
- **Operation Optimization**
- **Diagnostics**

Design Analysis and Optimization

Design optimization (improvement)
of an energy conversion system
=
Modification of the structure
and
the design parameters (operating conditions) of a system
to minimize the total levelized cost of the system products
under several *boundary conditions*.

Boundary Conditions

- Available materials
- Financial resources
- Protection of the environment
- Government regulation
- Safety, reliability, operability, availability, maintainability of the system

Operation Optimization

Capital investment represents sunk costs.

The average cost per unit exergy of fuel and product is used in the most important components to decide about changes in the system parameters that would improve the cost effectiveness of the overall system.

Diagnostics

A comparison of the actual values with the corresponding design values for the average cost per unit exergy of fuel and product for each component assists considerably in identifying malfunctioning components.

Optimization

A truly *optimized* (= *improved*) system is one for which the magnitude of every significant thermodynamic inefficiency (exergy destruction and exergy loss) is justified by considerations related to costs or is imposed by at least one of the *boundary conditions*.

Optimization Procedure

Objective function $\dot{C}_{P,tot} = min$ or $c_{P,tot} = min$

- **Complex energy conversion systems cannot usually be optimized using mathematical optimization techniques.**
- **The reasons include:**
  - ∗ **system complexity**
  - ∗ **opportunities for structural changes not identified during model development**
  - ∗ **incomplete cost models**
  - ∗ **plant safety, availability, maintainability and operability cannot be included in the model**

Thermoeconomic Techniques

Provide effective assistance in identifying, evaluating, and reducing the thermodynamic inefficiencies and costs in an energy conversion system.

Improve the engineer's understanding of the interactions among the system components and variables.

Reveal opportunities for design improvements that might not be detected by other methods.

Iterative Design Optimization

For each of the most important components, the engineer decides whether
(a) an increase in the efficiency at the expense of investment costs, or
(b) a decrease in the investment costs at the expense of the efficiency would increase the cost effectiveness of the overall system.

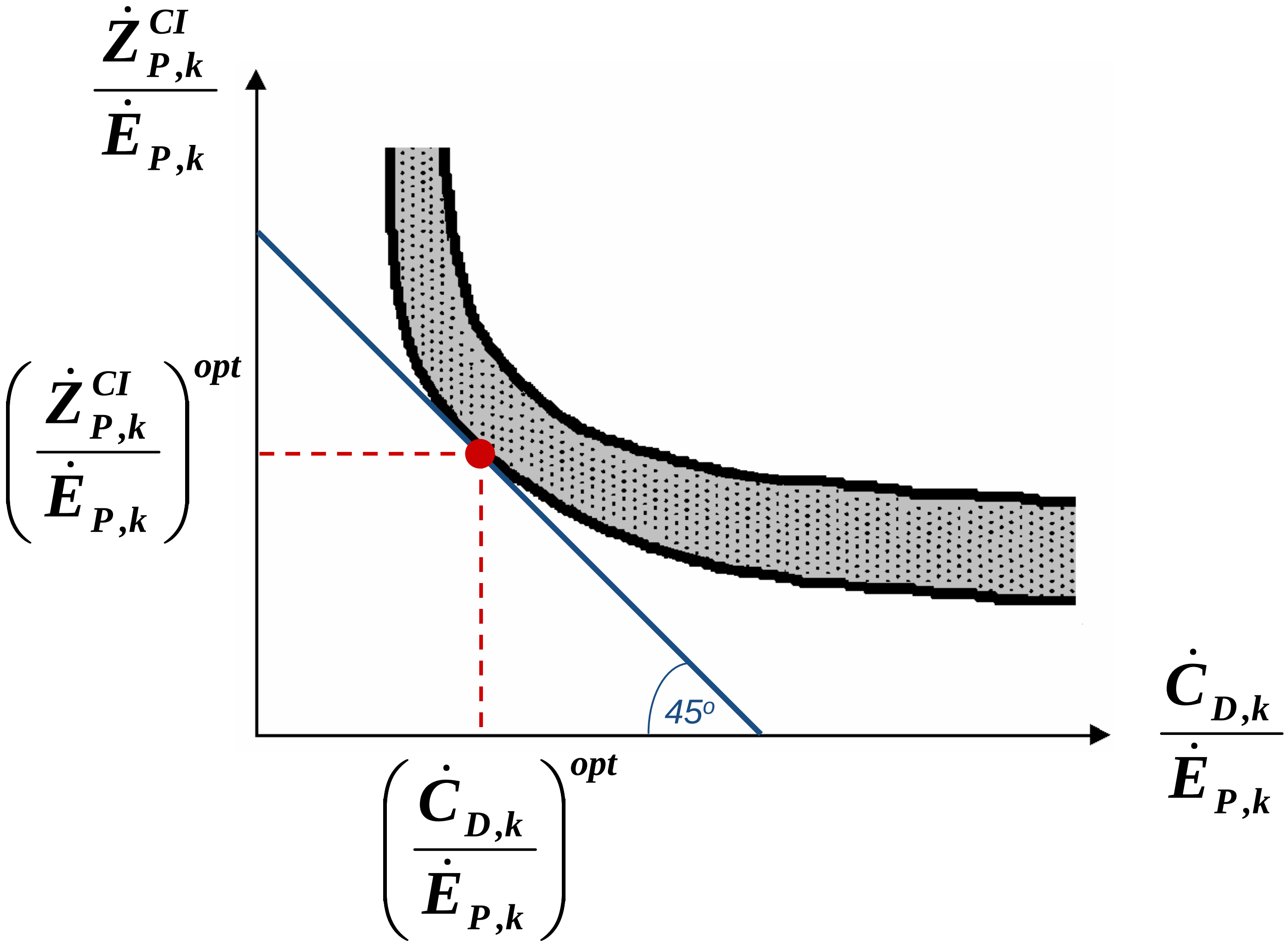
This decision is based on the actual values of *investment cost* and *cost of exergy destruction* and/or on a comparison between actual and cost optimal exergetic efficiency of the component being considered.

Component Evaluation

The evaluation of system components from the exergoeconomic viewpoint is based, in addition to the exergy based variables $\dot{E}_{D,k}$, ε_k and $y_{D,k}$, on the cost of exergy destruction $\dot{C}_{D,k}$ and on the capital investment cost $\dot{Z}_k$.

The sum of these two costs $\left(\dot{C}_{D,k} + \dot{Z}_k\right)$ determines the economic importance of the component being considered.

Component Evaluation



Component Evaluation

1. Rank the components in descending order of cost importance using the sum $\left(\dot{Z}_k + \dot{C}_{D,k}\right)$.

2. Consider initially design changes for the components for which the value of $\left(\dot{Z}_k + \dot{C}_{D,k}\right)$ is high.

3. Pay particular attention to components with high relative cost difference r_k, especially when the cost rates $\left(\dot{Z}_k + \dot{C}_{D,k}\right)$ are high.

Component Evaluation

4. **Use the exergoeconomic factor f_k to identify the major cost source (capital investment or cost of exergy destruction):**

If the f_k value is high, investigate whether it is cost effective to reduce the capital investment for the *k*-th component at the expense of the component efficiency.
If the f_k value is low, try to improve the component efficiency by increasing the capital investment.

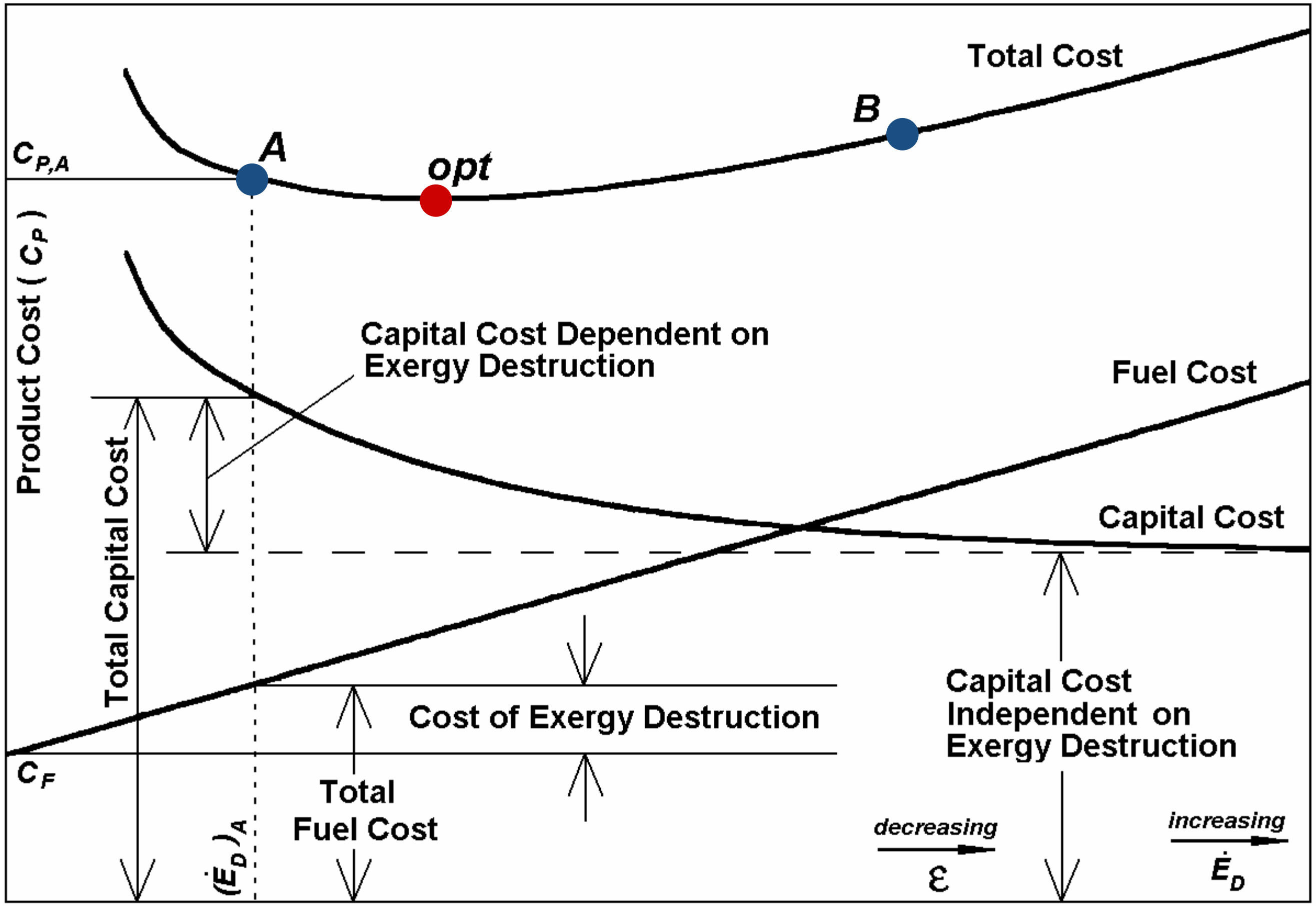
Component Evaluation

5. Eliminate any subprocesses that increase the exergy destruction within the k-th component without contributing to the reduction of capital investment or of fuel costs for other components.

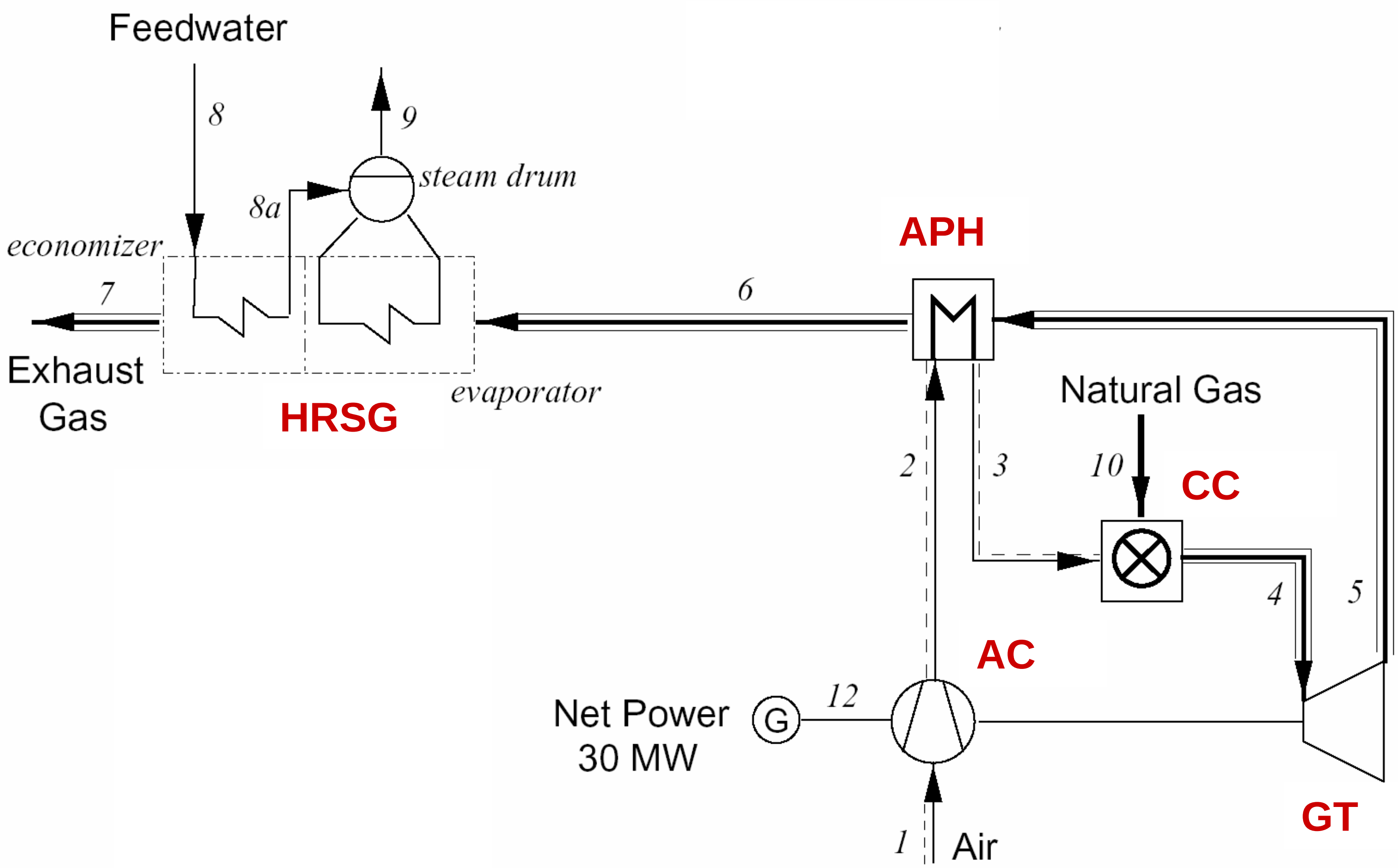
6. Consider improving the exergetic efficiency of the k-th component if it has a relatively low exergetic efficiency (ε_k) or a relatively large value for the rate of exergy destruction $(\dot{E}_{D,k})$, or the exergy destruction ratio $y_{D,k}$.

Exergoeconomic Concept

Schematic of the contribution of fuel and capital cost to the total product cost, as a function of the exergetic efficiency and exergy destruction



Design Optimization: Cogeneration System



Design Optimization: Cogeneration System

Value of the decision variables and selected parameters for the base design, thermodynamically optimal (TO) design, and cost-optimal design

Parameter	Base Design	TO Design	CO Design
Compressor pressure ratio, p_2/p_1	10.0	16.0	6.0
Compressor isentropic efficiency, η_{cs} (%)	86.0	88.0	81.1
Turbine isentropic efficiency, η_{ts} (%)	86.0	90.0	84.7
Air preheater outlet temperature, T_3 (K)	850.0	792.4	903.0
Combustion products temperature, T_4 (K)	1520.0	1550.0	1462.9
Pinch temperature difference in the HRSG, $\Delta T_{min,hrsg}$ (K)	40.2	15.0	50.8
Air mass flow rate, $\dot{m}_1$ (kg/s)	91.28	74.23	122.20
Methane mass flow rate, $\dot{m}_{10}$ (kg/s)	1.64	1.51	1.83

Design Optimization: Cogeneration System

Variables of the exergetic analysis for the *k*-th component of the cogeneration system for the base design and the TO and CO designs

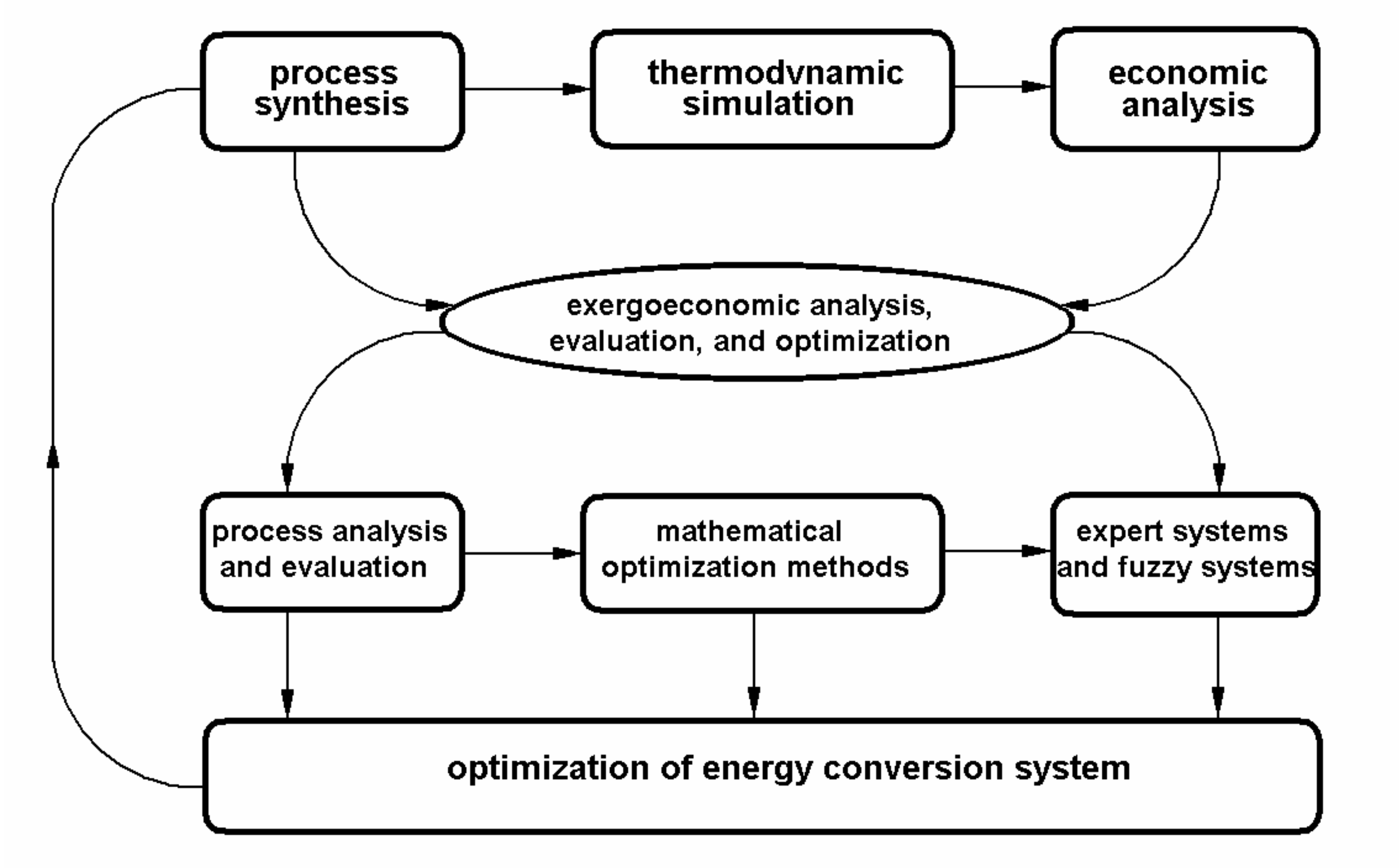
	Base Design			TO Design			CO Design		
Component	$\dot{E}_{D,k}$ (MW)	$\frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$ (%)	ε (%)	$\dot{E}_{D,k}$ (MW)	$\frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$ (%)	ε (%)	$\dot{E}_{D,k}$ (MW)	$\frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$ (%)	ε (%)
Combustion chamber	25.75	30.20	79.8	23.81	30.32	78.8	28.70	30.48	80.8
Heat-recovery steam generator	6.23	7.31	67.2	5.58	7.10	69.6	6.33	6.67	66.8
Gas turbine	3.01	3.53	95.2	2.29	2.91	96.4	3.16	3.33	95.0
Air preheater	2.63	3.08	84.6	1.08	1.38	82.8	5.31	5.60	84.3
Air compressor	2.12	2.49	92.8	1.66	2.11	94.6	3.36	3.54	89.0
Total system	39.74	46.61	50.1	34.42	43.83	54.4	46.86	49.63	45.1

Design Optimization: Cogeneration System

Calculated costs for the base design, thermodynamically optimal (TO) design, and cost-optimal (CO) design

Parameter	Base Design	TO Design	CO Design
Total cost flow rate ($/h)	3617	9089	2870
Cost of electricity (¢/kWh)	7.41	21.34	5.55
Cost of steam (¢/kg)	2.77	5.33	2.39

Exergoeconomics in Optimization Procedure



Advanced Exergoeconomics

$$\dot{E}_{D,k}$$

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

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

$$\dot{Z}_{k}$$

$$\dot{Z}_{k}^{EN} + \dot{Z}_{k}^{EX} \qquad \dot{Z}_{k}^{UN} + \dot{Z}_{k}^{AV}$$

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

To better understand the interactions among different components of the same system and to improve the quality of the conclusions obtained from an exergoeconomic evaluation, the exergy destruction in each (important) system component as well as the investment cost associa-ted with such component is split into *endogenous/ exogenous* and *unavoidable/avoidable* parts.