Minimization of Costs and Environmental Impact Using Exergy-Based Methods

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Conference “The Future for Sustainable Built Environments with High Performance Energy Systems”
München • October 21, 2010

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The objective evaluation and the improvement of an energy conversion system from the viewpoints of thermodynamics, economics, and environmental impact require a deep understanding of:

- the real thermodynamic inefficiencies and the processes that cause them,
- the costs associated with equipment and thermodynamic inefficiencies as well as the connection between these two important factors,
- the environmental impact associated with equipment and thermodynamic inefficiencies as well as the connection between these two sources of environmental impact,
- the interconnections among efficiency, investment cost and component-related environmental impact associated with the selection of specific system components, and
- possible measures that would improve the efficiency and the cost effectiveness and would reduce the environmental impact of the system being studied.
**Introduction - 2**

*Energy-based methods* are not suitable for answering these questions because the only thermodynamic inefficiencies identified by energy-based methods are the transfer of energy to the environment. However, *the inefficiencies caused by the irreversibilities within the system* being considered are, in general, by far the most important thermodynamic inefficiencies and are identifiable with the aid of an exergetic analysis.

If we want to successfully reduce thermodynamic inefficiencies, cost and environmental impacts in a system we must first understand their formation process. *Exergy-based methods* reveal the location, the magnitude and the sources of inefficiencies, costs and environmental impact and allow us to study the interconnections between them.
**Exergy-based methods** is a general term that includes the conventional and advanced *exergetic, exergoeconomic*, and *exergoenvironmental analyses* and evaluations.

The *concept of exergy* complements and enhances an energetic analysis by calculating

(a) the true thermodynamic value of an energy carrier,
(b) the real thermodynamic inefficiencies in a system, and
(c) variables that unambiguously characterize the performance of a system (or one of its components) from the thermodynamic viewpoint.
An **exergoeconomic analysis** (term proposed for the first time in 1984) consists of an exergetic analysis, an economic analysis, and an exergoeconomic evaluation.

**Exergoeconomics** is based on the **exergy costing principle**, which states that exergy is the only rational basis for assigning monetary values to energy streams and to the thermodynamic inefficiencies within the system.

Mass, energy or entropy should not be used for assigning monetary values because their exclusive use results in misleading conclusions.
Each Institution uses its own method for conducting an economic analysis.

An *economic analysis* should be conducted for the entire life of the system being considered. In this analysis, all pertinent costs should be considered. These include depreciation, return on debt and equity, taxes and insurance, fuel costs and operating and maintenance expenses. To obtain a representative year of system operation, all costs are levelized.
The real cost sources (identifiable only by exergoeconomics) in an energy conversion system are the:

- capital investment for each component
- operating and maintenance expenses
- cost of exergy destruction
- cost of exergy loss from the overall system
An **exergoenvironmental analysis** (presented for the first time in 2006) consists of an exergetic analysis, a life cycle assessment (LCA) of the environmental impact and an exergoenvironmental evaluation conducted in analogy with the exergoeconomic one.

The **exergoenvironmental costing principle** which is used in an exergoenvironmental analysis, states that exergy is the only rational basis for assigning environmental impact to energy streams and to the thermodynamic inefficiencies within a system.
Life Cycle Assessment

The total system used to conduct the LCA includes the supply of the input streams, especially the fuel, and the full life cycle of components. Inventories of elementary flows – i.e., consumption of natural resources and energy as well as emissions - are compiled following the guidelines of international standard approaches.

An impact assessment is performed using an environmental indicator (e.g., the *Eco-indicator 99*, which is based on the definition of three damage categories, human health, ecosystem quality and natural resources).

The result is expressed as *Eco-indicator points (pts)*.
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 cost and sometimes also the environmental impact associated with the component being considered and, thus, with the overall system.
The **conventional exergetic**, **exergoeconomic**, and **exergo-environmental** analyses do not evaluate the mutual interdependencies among the system components nor the potential for improving a component.

These issues are considered in the **advanced analyses**, in which the **exergy destruction**, **capital investment cost** and **construction-of-component-related environmental impact** in each component are split into:

- **Endogenous** and **exogenous** parts,
- **Unavoidable** and **avoidable** parts, and
- The resulting combined parts.
The *endogenous* exergy destruction in a component \( \dot{E}^{EN}_{D,k} \) refers to the irreversibility occurring within this component when all other components operate in an ideal way and the component being considered operates with its current efficiency.

The *exogenous* exergy destruction \( \dot{E}^{EX}_{D,k} \) is caused in the \( k \)-th component by the irreversibilities that occur in the remaining components.

\[
\dot{E}_{D,k} = \dot{E}^{EN}_{D,k} + \dot{E}^{EX}_{D,k}
\]
**Definition of** $\dot{E}_{D,k}^{UN}$ **and** $\dot{E}_{D,k}^{AV}$

*Unavoidable* ($\dot{E}_{D,k}^{UN}$) is the exergy destruction in a component that will always be there as long as this component is being used in the system, i.e. the unavoidable exergy destruction cannot be reduced because of technological limitations such as availability and cost of materials and manufacturing methods.

The *avoidable* exergy destruction ($\dot{E}_{D,k}^{AV}$) can be varied during efforts to improve the cost effectiveness of the component and the overall system.
Cannot be reduced because of technical limitations in the $k$-th component or in other components of the overall system for the given structure.

**AV,EN** - can be reduced through an improvement of the efficiency of the $k$-th component.

**AV,EX** - can be reduced by a structural optimization of the overall system or by improving the efficiency of the remaining components.

\[ \frac{\dot{C}_{D,k}}{\dot{E}_{P,k}} = \frac{c_{F,k}(\dot{E}_{D,k})}{\dot{E}_{P,k}} \]
Splitting the Exergy Destruction

\[ \dot{E}_{D,k}^{EX,1} + \ldots + \dot{E}_{D,k}^{EX,n} + \dot{E}_{D,k}^{mexo} \]

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

\[ \dot{E}_{D,k}^{UN,EN} \]

\[ \dot{E}_{D,k}^{UN,EX} \]

\[ \dot{E}_{D,k}^{AV,EN} \]

\[ \dot{E}_{D,k}^{AV,EX} \]

\[ \dot{E}_{D,k}^{AV,EX,1} + \ldots + \dot{E}_{D,k}^{AV,EX,n} + \dot{E}_{D,k}^{AV,mexo} \]
Example: Refrigeration machine

\[ Q_{cold} = 50 \text{ kW} \]

**Working fluid:** R134a

**Water:** \( T_8 = 5^\circ \text{C} \) und \( T_9 = 12^\circ \text{C} \)

**Water:** \( T_6 = 20^\circ \text{C} \) und \( T_7 = 25^\circ \text{C} \)

<table>
<thead>
<tr>
<th>Stream</th>
<th>Working fluid</th>
<th>( m ) [kg/s]</th>
<th>( T ) [K]</th>
<th>( p ) [bar]</th>
<th>( e ) [kJ/kg]</th>
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<tr>
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<td>1.704</td>
<td>5</td>
<td>1.42</td>
<td>1.71</td>
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Example: Refrigeration machine

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{E}^{\text{real}}_{F,k}$ [kW]</th>
<th>$\dot{E}^{\text{real}}_{P,k}$ [kW]</th>
<th>$\dot{E}^{\text{real}}_{D,k}$ [kW]</th>
<th>$\varepsilon_k$ [%]</th>
<th>$\gamma_k$ [%]</th>
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<td>0.496</td>
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<td>-</td>
<td>24.3</td>
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<td>3.864</td>
<td>0.994</td>
<td>79.5</td>
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<tr>
<td>EV</td>
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<td>2.031</td>
<td>1.626</td>
<td>55.5</td>
<td>19.0</td>
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### Example: Conventional Analyses

#### Conventional exergoeconomic analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>$PEC_k$ [€]</th>
<th>$\dot{Z}_k$ [€ cent/h]</th>
<th>$\dot{C}_{D,k}$ [€ cent/h]</th>
<th>$\dot{Z}<em>k + \dot{C}</em>{D,k}$ [€ cent/h]</th>
<th>$c_{F,k}$ [€/GJ]</th>
<th>$c_{P,k}$ [€/GJ]</th>
<th>$r_k$ [-]</th>
<th>$f_k$ [%]</th>
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<tr>
<td>CM</td>
<td>9 370</td>
<td>14.3</td>
<td>13.8</td>
<td>28.1</td>
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<td>50</td>
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<td>15.9</td>
<td>44.10</td>
<td>55.50</td>
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<td>55.50</td>
<td>103.70</td>
<td>0.87</td>
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#### Conventional exergoenvironmental analysis

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<tr>
<th>Component</th>
<th>$Y_k$ [mPts]</th>
<th>$\dot{Y}_k$ [mPts/h]</th>
<th>$\dot{B}_{D,k}$ [mPts/h]</th>
<th>$\dot{Y}<em>k + \dot{B}</em>{D,k}$ [mPts/h]</th>
<th>$b_{F,k}$ [mPts/GJ]</th>
<th>$b_{P,k}$ [mPts/GJ]</th>
<th>$r_{b,k}$ [-]</th>
<th>$f_{b,k}$ [%]</th>
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<td>15.60</td>
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<tr>
<td>CD</td>
<td>108 382</td>
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<td>33.56</td>
<td>4 377</td>
<td>23 160</td>
<td>4.29</td>
<td>2.50</td>
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<tr>
<td>TV</td>
<td>172</td>
<td>0.001</td>
<td>15.34</td>
<td>15.35</td>
<td>4 289</td>
<td>5 392</td>
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<tr>
<td>EV</td>
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<td>5 392</td>
<td>9 808</td>
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<td>2.26</td>
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</table>
## Example: Advanced Exergetic Analysis

Advanced exergetic analysis for the vapor-compression refrigeration machine

<table>
<thead>
<tr>
<th>Component</th>
<th>$\dot{E}_{in}$ [W]</th>
<th>$\dot{E}_{ex}$ [W]</th>
<th>$\dot{E}_{cm}$ [W]</th>
<th>$\dot{E}_{av}$ [W]</th>
<th>Splitting $\dot{E}_{ex}$ [W]</th>
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<tbody>
<tr>
<td>CM</td>
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<td>371</td>
<td>802</td>
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<td></td>
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<td></td>
<td></td>
<td>166</td>
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<tr>
<td>TV</td>
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<td>2</td>
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<tr>
<td>EV</td>
<td>208</td>
<td></td>
<td></td>
<td></td>
<td>66</td>
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<tr>
<td>mexo</td>
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<tr>
<td>CD</td>
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<td>278</td>
<td>60</td>
<td>1,457</td>
<td>538</td>
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<td>52</td>
</tr>
<tr>
<td>TV</td>
<td>24</td>
<td></td>
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<td></td>
<td>8</td>
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<tr>
<td>EV</td>
<td>150</td>
<td></td>
<td></td>
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<td>27</td>
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<td>mexo</td>
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<tr>
<td>TV</td>
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<tr>
<td>TV</td>
<td>23</td>
<td></td>
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<td></td>
<td>23</td>
</tr>
<tr>
<td>mexo</td>
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<tr>
<td>EV</td>
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<td>756</td>
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<td>756</td>
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</table>

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### Example: Refrigeration machine

#### Summary of the results obtained from the advanced exergy-based analyses.

<table>
<thead>
<tr>
<th>Component</th>
<th>Advanced exergetic analysis</th>
<th>Advanced exergoeconomic analysis</th>
<th>Advanced exergoenvironmental analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\dot{B}_{D,k}$ [kW]</td>
<td>$\dot{D}_{E,k}$ [cent/h]</td>
<td>$\dot{C}<em>{A</em>{E,k}}$ [cent/h]</td>
</tr>
<tr>
<td>CM</td>
<td>835</td>
<td>5.6</td>
<td>11.31</td>
</tr>
<tr>
<td>CD</td>
<td>1382</td>
<td>3.2</td>
<td>21.63</td>
</tr>
<tr>
<td>TV</td>
<td>20</td>
<td>0.0</td>
<td>1.90</td>
</tr>
<tr>
<td>EV</td>
<td>1133</td>
<td>3.9</td>
<td>21.65</td>
</tr>
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</table>
The *methods* discussed here *enable* engineers to

- calculate the flow of exergy, cost and environmental impact through the plant
- identify the real sources of thermodynamic inefficiencies, costs, and environmental impacts
- calculate the cost and the environmental impact associated with exergy destruction at the component level
- decide about well justified design changes
With these methods

- A plant can be analyzed in a consistent way from the viewpoints of thermodynamics, economics and environmental impact.
- The connections between thermodynamics and economics are revealed, and
- The interactions among plant components and the potential for improving a component and the overall system are also identified.

The connections between environmental impact on one side and thermodynamics or economics on the other side still need to be studied.
With the methods presented here

- our understanding of what is really going on in an energy conversion process is greatly improved, and

- the knowledge, experience, creativity, and confidence (during the decision-making process) of an engineer are enhanced.
Thank you for your attention
Appendix
Refrigeration machine for an air-condition system
Methodology for Splitting

The methodology for splitting the exergy destruction and the investment cost into endogenous/exogenous and avoidable/unavoidable parts and their combinations is based in this example on thermodynamic cycles (processes).

The following thermodynamic cycles are needed:

The real cycle (process)

The theoretical cycle (process) that corresponds to the given real cycle

The cycle (process) with unavoidable exergy destruction

The cycle (process) with unavoidable investment cost

The hybrid cycles (processes).

The hybrid cycle contains only one process which is conducted with the same efficiency as in the real cycle while all other processes correspond to the theoretical cycle.
Refrigeration machine. Methodology:
UN Exergy Destruction and Cost - 1
Refrigeration machine. Methodology: UN Exergy Destruction and Cost - 2
Refrigeration machine. Methodology: EX Exergy Destruction and Cost

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

\[ \dot{E}_{D,k}^{EX} + \dot{E}_{D,k}^{EX} = \dot{E}_{D,k}^{EX,(n+1)} \]

\[ \dot{E}_{D,k}^{EX} > \dot{E}_{D,k}^{EX,(n-1)} + \dot{E}_{D,k}^{EX,(n)} + \dot{E}_{D,k}^{EX,(n+1)} \]

\[ \dot{E}_{D,k}^{EX} = \dot{E}_{D,k}^{EX,(n-1)} + \dot{E}_{D,k}^{EX,(n)} + \dot{E}_{D,k}^{EX,(n+1)} + \dot{E}_{D,k}^{MX} \]

Mexogenous Exergy Destruction
Exergetic Variables: $E_P$ and $E_F$

**Exergy of product:** $\dot{E}_P$

The desired result, expressed in exergy terms, achieved by the system (the $k$-th component) being considered.

**Exergy of fuel:** $\dot{E}_F$

The exergetic resources expended to generate the exergy of the product.

The concepts of product and fuel are used in a consistent way not only in *exergetic analyses* but also in the *exergoeconomic* and *exergoenvironmental* analyses.
**Exergetic Variables:** $E_D$ and $E_L$

**Exergy destruction:** $\dot{E}_D$

Exergy destroyed due to irreversibilities within a system (the $k$-th component).

**Exergy loss:** $\dot{E}_L$

Exergy transfer to the system surroundings. This exergy transfer is not further used in the installation being considered or in another one.

**Exergy balance:**

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L$$

$\dot{E}_D$ and $\dot{E}_L$ are absolute measures of the thermodynamic inefficiencies.
Relative measures:

**Exergetic efficiency**: The ratio between exergy of product and exergy of fuel

\[ \varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \]

**Exergy destruction ratio** for the \( k \)-th component

\[ y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}} \]
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

\[ \dot{C}_j = c_j \dot{E}_j \]

\( \dot{C}_j \) = cost stream; \( \dot{E}_j \) = exergy stream; 
\( c_j \) = average cost per unit of exergy
Cost balance applied to the $k$-th system component

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

\[
c_{P,k} \dot{E}_{P,k} = c_{F,k} \dot{E}_{F,k} + \dot{Z}_k
\]
The real cost sources in an energy conversion system are:

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

\[
\dot{Z}_k = \dot{Z}^{CI}_k + \dot{Z}^{OM}_k
\]

\[
\dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k} \quad \dot{C}_{D,tot} = c_{F,tot} \dot{E}_{D,tot}
\]

\[
\dot{C}_{L,tot} = c_{F,tot} \dot{E}_{L,tot}
\]
Environmental Impact Balance

\[
b_{p,k} \dot{E}_{p,k} = b_{F,k} \dot{E}_{F,k} + \dot{Y}_k
\]
The component-related environmental impact associated with the life cycle of the \( k \)-th component is

\[
\dot{Y}_k = \dot{Y}_{k\ CO} + \dot{Y}_{k\ OM} + \dot{Y}_{k\ DI}
\]

The environmental impacts that occur during the three life cycle phases construction (including manufacturing, transport and installation), operation and maintenance, and disposal constitute the component-related environmental impact \( \dot{Y}_k \) of the \( k \)-th component.

All values of environmental impact are obtained by LCA.
**Exergoeconomic 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**

\[
    f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k} \dot{E}_{D,k}}
\]
Variables of the exergoenvironmental analysis

Relative difference between the average environmental impact per exergy unit of product and average environmental impact per exergy unit of fuel

\[ r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} = \frac{b_{F,k} \dot{E}_{D,k} + \dot{Y}_k}{b_{F,k} \dot{E}_{P,k}} = \frac{1 - \varepsilon_k}{\varepsilon_k} + \frac{\dot{Y}_k}{b_{F,k} \dot{E}_{P,k}} \]

Exergoenvironmental factor

\[ f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + B_{D,k}} = \frac{\dot{Y}_k}{\dot{Y}_k + b_{F,k} \dot{E}_{D,k}} \]
Similar definitions apply also to the *endogenous* \( \hat{Z}_k^{EN} \) and \( \hat{Y}_k^{EN} \) and *exogenous* \( \hat{Z}_k^{EX} \) and \( \hat{Y}_k^{EX} \) investment cost and construction-of-component-related environmental impact

\[
\hat{Z}_k = \hat{Z}_k^{EN} + \hat{Z}_k^{EX}
\]

\[
\hat{Y}_k = \hat{Y}_k^{EN} + \hat{Y}_k^{EX}
\]
The *unavoidable* investment cost and (\(\dot{Z}_k^{UN}\)) for a component can be calculated by assuming an extremely inefficient version of this component.

The *unavoidable* component-related environmental impact (\(\dot{Y}_k^{UN}\)) is calculated using the minimal environmental impact from each category.

To adjust for different component sizes, we calculate for each component the unavoidable cost or unavoidable construction-of-component-related environmental impact per unit of exergy of the product \((\dot{Z} / \dot{E}_P)_k^{UN}\) or \((\dot{Y} / \dot{E}_P)_k^{UN}\).
New Variables for the Advanced Exergy-Based Analyses

Sum of avoidable exergy destructions caused by the component being considered

\[
\dot{E}_{D,k}^{AV,\Sigma} = \dot{E}_{D,k}^{AV,EN} + \sum_{r=1}^{n} \dot{E}_{D,r}^{AV,EX,k} \\
\dot{C}_{D,k}^{AV,\Sigma} = \dot{C}_{D,k}^{AV,EN} + \sum_{r=1}^{n} c_{F,r} \cdot \dot{C}_{D,r}^{AV,EX,k} \\
\dot{Y}_{k}^{AV,\Sigma} = \dot{Y}_{k}^{AV,EN} + \sum_{r=1}^{n} \dot{Y}_{r}^{AV,EX,k} \\
\dot{B}_{D,k}^{AV,\Sigma} = \dot{B}_{D,k}^{AV,EN} + \sum_{r=1}^{n} b_{F,r} \cdot \dot{B}_{D,r}^{AV,EX,k}
\]
Exergy-Based Methods

- Exergoeconomic analysis
- Exergoenvironmental analysis

Exergy analysis

- Economic analysis
- Life cycle assessment

Exergoeconomic evaluation

Iterative improvement
Example: Refrigeration machine

\[\dot{Y}_{CM} = 0.191 \, \text{mPts/h}\]

\[\dot{Z}_{CM} = 7.90 \, \text{€/h}\]

\[\dot{E}_{D,CM} = \dot{W}_{CM} - (\dot{E}_2 - \dot{E}_{1a})\]

\[\dot{E}_{D,TV} = (\dot{E}_4 - \dot{E}_1) - (\dot{E}_9 - \dot{E}_8)\]

\[\dot{E}_{D,TV} = (\dot{E}_3^M - \dot{E}_4^M) - (\dot{E}_4^T - \dot{E}_3^T)\]

\[\dot{Z}_{TV} = 0.1 \, \text{€/h}\]

\[\dot{Y}_{TV} = 0.001 \, \text{mPts/h}\]

\[\dot{Y}_{CD} = 0.770 \, \text{mPts/h}\]

\[\dot{Z}_{CD} = 2.60 \, \text{€/h}\]
### Example: Refrigeration machine

#### Splitting the capital investment cost for components of the vapor-compression refrigeration machine

<table>
<thead>
<tr>
<th>Component</th>
<th>( \hat{Z}_k ) [€ cent/h]</th>
<th>( \hat{Z}_{EX} ) [€ cent/h]</th>
<th>( \hat{Z}_{UV} ) [€ cent/h]</th>
<th>( \hat{Z}_{AV} ) [€ cent/h]</th>
<th>Splitting ( \hat{z}_{reJ} ) [€ cent/h]</th>
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<tbody>
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Institute for Energy Engineering

G. Tsatsaronis • TU Berlin
Conference “The Future for Sustainable Built Environments with High Performance Energy Systems” • München • October 21 2010
### Example: Refrigeration machine

Splitting the capital investment cost for components of the vapor-compression refrigeration machine

<table>
<thead>
<tr>
<th>Component</th>
<th>$Y^{2N}_{k}$ [mPts/h]</th>
<th>$Y^{2X}_{k}$ [mPts/h]</th>
<th>$Y^{2D}_{k}$ [mPts/h]</th>
<th>$Y^{2A}_{k}$ [mPts/h]</th>
<th>$Y^{2R}_{k}$ [mPts/h]</th>
<th>$Y^{2V}_{k}$ [mPts/h]</th>
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