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Giving Anergy a Value by the Application of an Anergy-exergy Cost Ratio in Thermo-economic Analysis of Systems that Make Thermal Energy Available

Lutz Meyer[1,*] Ingo Stadler[2]

[1] *Institut für Verfahrenstechnik, Energietechnik und Klimaschutz, Hochschule Hannover / University of Applied Sciences and Arts*
[2] *Cologne Institute for Renewable Energy, Technische Hochschule Köln / University of Applied Science*
[*] *Corresponding author. Email: lutz.meyer@hs-hannover.de*

***Abstract*—Techno-economic analysis that allocate costs to the energy flows of energy systems are helpful to understand the formation of costs within processes and to increase the cost efficiency. For the economic evaluation, the usefulness or quality of the energy is of great importance. In exergy-based methods, this is considered by allocating costs to the exergy instead of energy. As exergy represents the ability of performing work, it is often named the useful part of energy. In contrast, the anergy, the part of energy, which cannot perform work, is often assumed to be not useful.**
However, heat flows as used e.g. in domestic heating are always a mixture of a relative small portion of exergy and a big portion of anergy. Although of lower quality, the anergy is obviously useful for these applications. The question is, whether it makes sense to differentiate between exergy and anergy and take both properties into account for the economic evaluation.
To answer this question, a new methodical concept based on the definition of an anergy-exergy cost ratio is compared to the commonly applied approaches of considering either energy or exergy as the basis for economic evaluation. These three different approaches for the economic analysis of thermal energy systems are applied to an exemplary heating system with thermal storages. It is shown that the results of the techno-economic analysis can be improved by giving anergy an economic value and that the proposed anergy-cost ratio allows a flexible adaptation of the evaluation depending on the economic constraints of a system.

Keywords: Exergy, Anergy, Techno-Economic Analysis, Low Exergy Heat Net, District Heating, Thermal Storage, Heat Pump

1. INTRODUCTION

The thermodynamic analysis of processes based only on energy flows through the system gives an incomplete picture as the quality of the energy is neglected. E.g., in a thermal power plant the energy flows of the generated electric power and of the waste heat are considered equivalent. Looking only on the energy it is quite irritating that the first one is distributed and sold to consumers while the latter one is rejected to the environment.

In this regard, the development of exergy analysis (e.g. [1]) was a great advance. Because the exergy of an energy flow represents its ability of performing work, it is often named the useful part of energy and it is often interpreted as a measure of the quality of energy. Looking now on the exergy flows the operation of again the thermal power plant seems to be sensible. It extracts exergy from a heat source and delivers it as electric power (pure exergy) to the grid and only a small amount of exergy is rejected as part of the waste heat.

The part of the energy, which cannot be converted to work, is considered as not useful. This part is the anergy (e.g. [2])[1] and the sum of the exergy and anergy flow are equal to the energy flow. It is not possible to obtain work from anergy because it is on

[1] The anergy concept is limited in this paper to thermal energy and heat transfer above reference temperature. A general application has got some limitations and might be problematic (see section 4).

the same energetic state (e.g. regarding the temperature) as the environment. All the energy, which is in equilibrium with the environment, is anergy.

For the economic evaluation of energy conversion processes, it is very useful to determine specific costs of all relevant energy flows within the process. This is done by allocating costs to the energy to obtain e.g. costs of generated electricity per energy unit. This approach might be problematic in case the usefulness or quality of energy flows is different in a considered system. This is the case for the electric power and waste heat in the mentioned thermal power plant.

The exergoeconomic analysis [3] for the investigation of energy conversion processes allocates all costs connected to a process to the exergy flows through the system resulting in characteristic specific costs of exergy throughout the whole process. No costs are allocated to the anergy flows, because the anergy is useless for generation of work. Regarding the analysis of a thermal power plant this method is very well suited.

For direct use of thermal energy, the situation is different. Heat flows as used e.g. in domestic heating are always a mixture of a relative small portion of exergy and a big portion of anergy. Obviously, the anergy is useful for these applications. Even anergy is useful it might not have any economic value, because our environment is an unlimited source of anergy. Nevertheless, technical systems like thermal storages and heat pumps are built to make anergy available. This technical effort is linked to investment and operation costs. An exemplary thermal system, which makes anergy-exergy flows available to generate a heat flow for a heating application is shown in Figure 3 (further explanation see part 3).

For an analysis of a process aimed at the generation of a heat flow, the two approaches based on energy or exergy flows as mentioned above are normally applied. In this paper, the question shall be discussed:

➔ Is it meaningful for the evaluation of thermal energy systems to differentiate between exergy and anergy flows and consider them both for allocating economic value?

As the basis for the discussion, the new methodical concept is compared to the established approaches for the economic analysis of thermal energy systems and all are applied to the mentioned exemplary heating system with thermal storage. The three approaches are:

- ***Case A***: Energy-based
  Energy flows are considered independent of the share of exergy and anergy. Therefore exergy and anergy are equivalent.
- ***Case B***: Exergy-based
  Only the exergy of the energy flows is considered. Therefore the anergy has no value.
- ***Case C***: Exergy-anergy-based (new approach)
  Both exergy and anergy are considered with a different value.

Comparing apples and oranges

Just looking at energy flows for the analysis of energy conversion processes is definitely like comparing apples and oranges (energy of high and low quality). For energy flows, it makes sense to adapt this metaphor a little bit by making exergy to “apples”, anergy to “applesauce”[2] and energy to any mixture of apples and sauce. This paper in fact wants to compare three perspectives:

- **Energetic perspective**: Looking at the mixture of apples and applesauce without considering the composition with respect to its usefulness
- **Exergetic perspective**: Looking just at the apples as useful and ignoring the applesauce
- **Exergetic and anergetic perspective**: Looking at apples and applesauce as food of different usefulness

2. METHODOLOGY

The objective of the method for the analysis of the exemplary system is to determine specific costs of energy flows (given e.g. in €/kWh) for all energy flows to make the formation of costs visible. The basic principle of this kind of techno-economic analysis is the allocation of costs to energy and is the same for all three approaches. The difference results from the chosen energetic basis for the three cases: energy, exergy, exergy + anergy. This means that for *case A* energetic costs, for *case B* exergetic costs and for *case C* exergetic and anergetic costs are determined. The energetic costs are determined additionally for *case B* and *case C* to make an easier comparison of the results possible.

[2] The idea of exchanging “oranges” with “applesauce” is considering the fact, that exergy can be converted to anergy but anergy not to exergy.

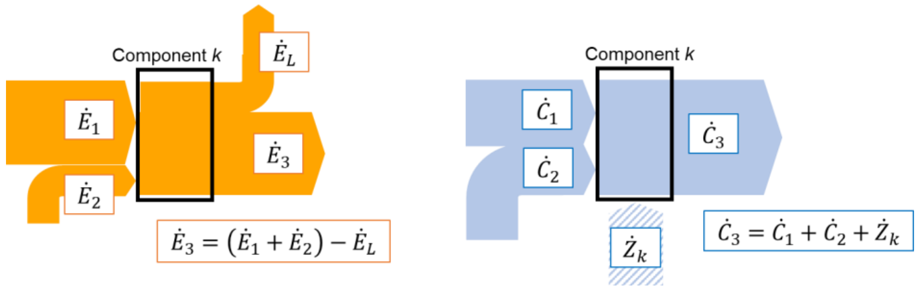

Figure 1 Energy and cost balance of an exemplary component *k*

The allocation of cost to exergy flows is a central element of the exergoeconomic analysis. The procedure applied here for all three cases is adopted in a simplified manner from "exergy costing" carried out in the framework of this method [4].

The cost allocation is done on the component level of a process. By connecting all process components based on energy flows, the entire process is analyzed. An energy and cost balance for all components *k* is the basis for the calculation of the specific costs of each energy flow.

2.1. Energy and cost balances of components

The formulation of the energy balance for the k^{th} component with input and output energy flows $\dot{E}_j$ and an energy loss $\dot{E}_L$ is[3]:

$$\sum \dot{E}_{j,in} = \sum \dot{E}_{j,out} + \dot{E}_L \tag{1}$$

The energy balance for the component *k* shown in Figure 1 is: $\dot{E}_1 + \dot{E}_2 = \dot{E}_3 + \dot{E}_L$

For the exergy and anergy flows the situation is different. The energy conservation holds only true for the energy (sum of exergy + anergy). In real components exergy is converted to anergy (e.g. due to heat transfer). Therefore, a part of the exergy is destroyed and anergy is generated. The corresponding flows of exergy destruction $\dot{Ex}_D$ and anergy generation $\dot{An}_G$ have to be considered in the calculation of the respective balance:

$$\sum \dot{Ex}_{j,in} = \sum \dot{Ex}_{j,out} + \dot{Ex}_L + \dot{Ex}_D \tag{2}$$

$$\sum \dot{An}_{j,in} = \sum \dot{An}_{j,out} + \dot{An}_L - \dot{An}_G \tag{3}$$

The idea behind calculating cost flows (or cost rates, given e.g. in €/s) is that each input flow (e.g. chemical energy of natural gas) to a production process is linked to certain costs and that during the entire process these flows add up to the costs linked to the product. In addition to the costs of inputs also costs connected to process units like capital and operation and maintenance costs can be considered.

In the k^{th} component the costs linked to the input flows $\dot{C}_{j,in}$ and the capital and O&M costs of the component $\dot{Z}_k$ add up and leave the component with output flows $\dot{C}_{j,out}$:

$$\sum \dot{C}_{j,in} + \dot{Z}_k = \sum \dot{C}_{j,out} \tag{4}$$

The cost balance for the component *k* shown in Figure 1 is: $\dot{C}_1 + \dot{C}_2 + \dot{Z}_k = \dot{C}_3$

For the exemplary analysis carried out in this paper the cost flow $\dot{Z}_k$ is not considered, because it is not relevant for the discussion how the anergy flows should be considered.

2.2. Allocation of costs to energy or exergy flows –energy or exergy costing

The allocation of cost flows to energy or exergy flows leads to the specific energetic or exergetic

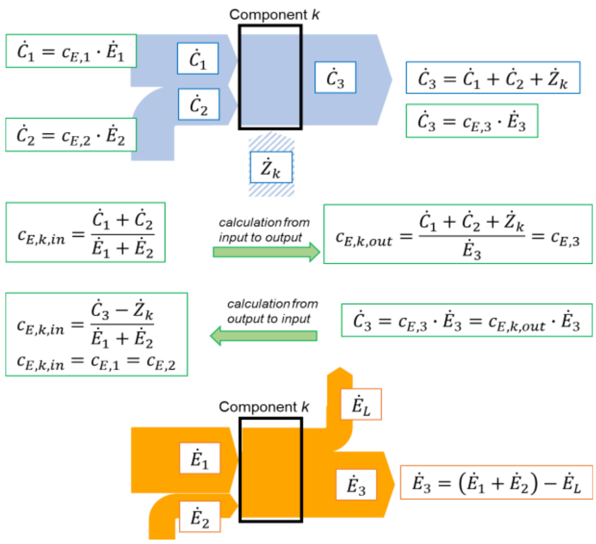

Figure 2 Energy based cost allocation for an exemplary component

[3] In the scientific "exergy"-community a different nomenclature is recommended [5](Tsatsaronis 2007). The deviation aims at facilitating the understanding for people outside this community.

costs, respectively (see Figure 2). The calculation can be carried out for any energy or exergy flow in a process (indepently if input or output).

Specific costs of the j^{th} flow – energy based (*Case A*):

$$c_{E,j} = \dot{C}_j / \dot{E}_j \tag{5}$$

Specific costs of the j^{th} flow – exergy based (*Case B*):

$$c_{Ex,j} = \dot{C}_j / \dot{E}x_j \tag{6}$$

Figure 2 shows the energy based cost allocation for an exemplary component *k*. First, the cost flows of the input, $\dot{C}_1$ and $\dot{C}_2$, are calculated based on their specific costs and energy. This allows determining the cost flow $\dot{C}_3$ and its specific costs $c_{E,3}$. The average specific costs of input and output are $c_{E,k,in}$ and $c_{E,k,out}$, respectively.

In case the costs shall be determined from input to output, the specific costs of all output flows are equal to the average specific costs of the output $c_{E,k,out}$.

If the calculation is carried out from output to input the average specific costs of the input $c_{E,k,in}$ can be calculated based on the cost flows $\dot{C}_3$, $\dot{Z}_k$ and the energy flows $\dot{E}_1$ and $\dot{E}_2$. The specific costs of all input flows are equal to the average specific costs of the input $c_{E,k,in}$.

2.3. Allocation of costs to exergy and anergy by an "anergy-exergy cost ratio"

For *case C* the costs have to be allocated to exergy and anergy flows and distributed between these two. As explained in the introduction, the idea of the new concept is that both exergy and anergy should be considered in a techno-economic evaluation. The distribution of costs should be done based on the different value (in other words usefulness) both parts of energy have for the analyzed process. It is assumed that it is sensible for a given system to define a constant ratio between anergetic and exergetic costs. The „**anergy-exergy cost ratio**" is defined as:

$$r_{An/Ex} = \frac{c_{An,j}}{c_{Ex,j}} \tag{7}$$

From a thermodynamic perspective, the value of the ratio should be less than one for any application. How a substantiated value can be determined is discussed later.

The distribution of the cost flow to exergy and anergy for *case C* leads to the following calculation of specific exergetic and anergetic costs of the j^{th} flow:

$$c_{Ex,j} = \dot{C}_{Ex,j} / \dot{E}x_j \tag{8}$$

$$c_{An,j} = \dot{C}_{An,j} / \dot{E}x_j \tag{9}$$

The total cost flow consists therefore of an exergetic and anergetic part:

$$\dot{C}_j = \dot{C}_{Ex,j} + \dot{C}_{An,j} = c_E \cdot \dot{E}_j \tag{10}$$

2.4. Determination of unknown specific output or input costs

The determination of costs for an entire process is carried out subsequently from component to component. For simple linear processes (as in the exemplary process analyzed here) the formulas are shown below. The calculation can start from known costs of input flows downstream until the product costs are determined. Alternatively, the calculation can start from defined product costs and the flows are calculated upstream until all input flows are defined.

When determining costs in downstream-direction, the specific costs for all outputs of a component are set equal which leads to (see Figure 2):

$$c_{E,k,out} = \frac{\sum \dot{C}_{j,out}}{\sum \dot{E}_{j,out}} = \frac{\sum \dot{C}_{j,in} + \dot{Z}_k}{\sum \dot{E}_{j,out}} \tag{11}$$

When the determination takes place in upstream-direction, the specific costs for all inputs are assumed to be equal:

$$c_{E,k,in} = \frac{\sum \dot{C}_{j,in}}{\sum \dot{E}_{j,in}} = \frac{\sum \dot{C}_{j,out} - \dot{Z}_k}{\sum \dot{E}_{j,in}} \tag{12}$$

The calculation is only shown for energetic costs. For exergetic and anergetic costs (*case B* and *case C*) the calculation is analogous.

2.5. Calculation of energetic values

The calculation of exergy and especially anergy values cannot be found in all thermodynamic textbooks. The details for the calculation as applied here are described in the given references ([6], [2]).

Only the general definition for anergy formulated for the energy flow of the j^{th} flow shall be shown:

$$\dot{A}n_j = \dot{E}_j - \dot{E}x_j \tag{13}$$

2.6. The value of apples and applesauce

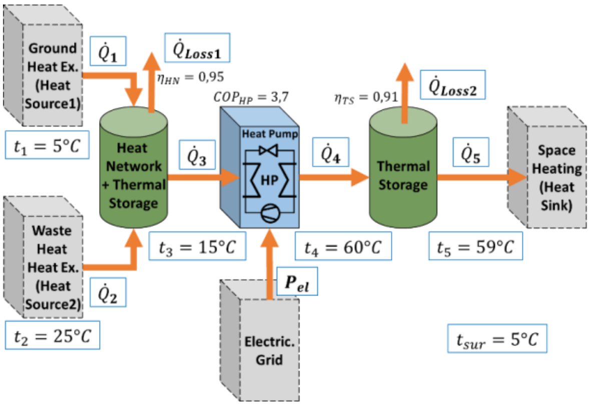

Figure 3 Heating system

What is the effect of the different methodic approaches for our metaphor and for the value of apples and applesauce? For *case A* the value of any mixture of apples and applesauce depends only on the total amount and is independent of the share of the two components. For *case B* only apples have a value and the costs of the mixture depend therefore only on the apple content. For *case C*, the applesauce has a value lower than the apples and the value of the mixture depends on the share of each component.

3. ANALYSIS OF THE EXEMPLARY HEATING SYSTEM

3.1. Description of the system

The analysis is aimed at studying the effects of considering the anergy within a thermo-economic analysis. As example a heating system, which includes a heat pump, has been chosen (Figure 3). The process delivers heat, a mixture of exergy and anergy, to a consumer. Due to the heat pump, it applies also heat as an energy input. Therefore, anergy and exergy flows are relevant for the entire process.

The heat generated by the heat pump is transferred to thermal storage and from there it is delivered to supply heaters or to heat up fresh water. The heat pump is coupled to a low temperature district heating (also known as lowex or anergy network). The network consists of a thermal storage and two heat sources. One heat source delivers heat at ambient temperature using a ground heat exchanger. The other source is waste heat e.g. from an industrial process.

Regarding the heat pump and heat consumer, this kind of systems are already widely used for private homes. Regarding the heat source the concept is rather in development stage. As it allows implementing an energy-efficient and carbon-free heating for apartment houses, several studies have been carried out to analyze low temperature district heating (e.g. [7], [8]).

Figure 3 shows the heat flows $\dot{Q}_j$ in the process, the transfer of electric energy P_{el} to the heat pump, and the temperature at which the heat is transferred from the heat source. These temperatures are applied for calculating the exergy of the heat. For simplification, it is assumed that they are constant.

The heating system has been designed in a way that by mixing the heat of source 1 and 2 the resulting temperature of $\dot{Q}_3$ is 10°C lower than the temperature of $\dot{Q}_2$. A change of temperature t_2 leads to a change in t_3 and to a different share of $\dot{Q}_1$ and $\dot{Q}_2$ in the total heat input. To fulfill the energy balance the share of $\dot{Q}_2$ increases with increasing temperature t_3. In section 3.4 the effect of varying the heat source temperatures is analyzed.

For the heat storages, an efficiency has been considered that is defined as the ratio of heat output and input:

$$\eta_{Storage} = \dot{Q}_{out}/\dot{Q}_{in} \tag{14}$$

The coefficient of performance COP of a heat pump expresses the ratio between the amount of heat that can be delivered and the electrical power that is consumed. A heat pump, that works according to a Carnot-Cycle, has the highest possible coefficient of performance. This COP_{Carnot} depends on the temperatures of heat source and sink. For the heat pump of the analyzed process, the assumption has been made that it reaches 50% of the performance of

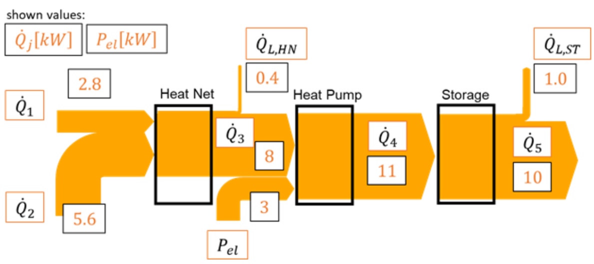

Figure 4 Energy flows in the heating system

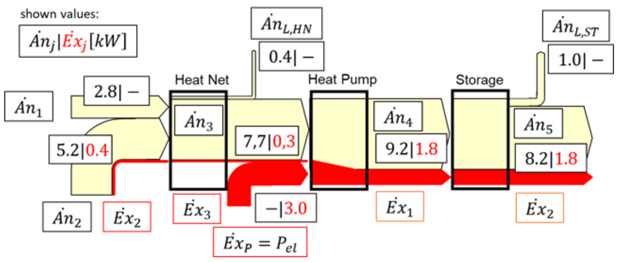

Figure 5 Exergy and anergy flows in the heating system

an ideal heat pump:

$$COP_{HP} = \dot{Q}_4/P_{el} = 0.5 \cdot COP_{Carnot} \quad (15)$$

The calculations of exergy and anergy flows for the heat pump are based on [6].

3.2. Energy flows

The calculated energy flows are represented in Sankey-diagrams (Figure 4 and 5). Energy flows (as heat $\dot{Q}_j$ and electric power P_{el}) are shown in orange, exergy flows $\dot{E}x_j$ in red and anergy flows $\dot{A}n_j$ in light yellow.

The energy flows in Figure 4 visualize how much energy is taken from each of the energy sources. Nevertheless, as discussed in the introduction, there is no information about the quality of the consumed energy. All sources seem to be equivalent. A comparison based on the energy flows with e.g. a conventional gas fired heating system would not be very meaningful.

Figure 5 shows clearly that the heat flow generated is a mixture of a relative big amount of anergy and a small amount of exergy. The diagram makes also the origin of the exergy visible and where it is destroyed and converted to anergy. Because exergy cannot be generated within a process, it has to be supplied as an input. Sources are the second heat source (above ambient temperature) and the electric power. Exergy destruction takes place in the heat pump due to irreversible operation, which is considered by the defined COP_{HP}, and due to heat transfer and heat losses in the storages, which lead to a temperature decrease. The exergy destruction in the heat network / thermal storage 1 and the thermal storage 2 is rather small. Therefore, the exergy destruction is not visible in the diagram. In general, the exergetic efficiency of the process seems to be quite good, as a great amount of the needed anergy is supplied to the system as anergy. Conventional heating systems, like the ones that burn fossil fuels, generate the anergy needed for heating by destroying exergy of the fuel.

3.3. Cost flows and specific energetic costs

The definition of specific costs $c_{E,5}$ of the generated heat $\dot{Q}_5$ has been the starting point for the calculation. We assume that the heat is supplied for $c_{E,5} = 0{,}1 \frac{€}{kWh} = 10 \frac{ct}{kWh}$ to the consumer. This value has been chosen to simplify comparisons and transfer of the results. Nevertheless, it is in the range of current average district heating costs in Germany. Going upstream the process, all cost flows and specific costs can be determined as described in section 2.4. The calculated specific costs of the input flows can be interpreted as their maximum acceptable costs for the generation of heat for the given value c_5.

As the energy flows, the cost flows $\dot{C}_j$ are represented as arrows in Sankey-diagrams for all cases (Figure 6). In addition, the diagrams show the specific energetic costs $c_{E,j}$ of all flows that have been calculated by applying equation (5). The energetic costs are the best basis for a comparison of the three approaches because they can be calculated for all cases and because they are commonly used in economic evaluations. However, it is important to mention, that for *case B* and *case C* the cost flows depend on the exergetic and anergetic costs and that the cost flows are the basis for the energetic costs. An overview of the all calculated specific costs is given in Table 1.

The flows and specific costs are identical from the output up to the heat pump. Quite different is the picture for the cost flows linked to the heat and electric power input of the heat pump and for the flows linked to the heat from the two heat sources.

In *case A* anergy and exergy are equivalent. Therefore, the cost flows of heat and electric power depend only on their energy content. The specific costs for all flows are identically and change only due to energy losses, which reduce the total amount of energy. The acceptable costs for the consumed electricity are in the same range as the costs of the two heat sources. These results confirm that an economic analysis based on just the energy is not meaningful in case energy of different quality is supplied or generated by a process.

For *case B* only the exergy is linked to an economic value and all anergy flows are economically neglected. As a result, for the electricity (pure exergy) rather high costs would be acceptable, but a heat input at very low costs would be needed. The energy supplied at ambient temperature (pure anergy, heat source 1) should not generate any costs. The exergoeconomic approach, realized for *case B*, seems to be more useful for a realistic determination of economic values of energy flows. Nevertheless, the calculated values indicate that in case low quality energy (low exergy share) is relevant, the results might be misleading. This might be especially the case if a certain economic effort is needed to make energy with low (or no) exergy content available or if exergy can be supplied at rather low costs.

The concept for *case C* is that anergy and exergy both have a different value for the system and the difference is defined by the anergy-exergy ratio (see section 2.3). For the analysis carried out here, as a first guess, it has been assumed that the value of exergy is four time as high as the value of anergy, which leads to the ratio $r_{An/Ex} = 0.25$. For the investigation of the general feasibility of the approach, the exact figure of the ratio is not important. The effect of changing the ratio is the topic of section 3.5.

Regarding the specific energetic costs the values for *case C* are in between *case A* and *B* (see section 3.5). The range of the results for the input energy flows seems to be reasonable in comparison with the assumed value for the generated heat. The acceptable costs for electricity are significantly higher than the energetic costs of the supplied heat. Nevertheless, the heat flows have a value that justifies a technical effort to make them available. Only with the new approach it is possible considering a value for a heat flow depending on its exergy content and avoiding a value of zero or close to zero for low-exergy heat at the same time.

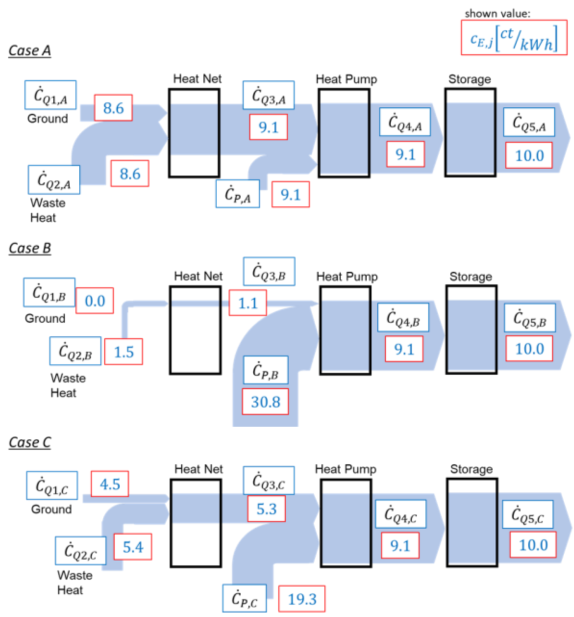

Figure 6 Cost flows and specific energetic costs

Table 1 Specific costs of energy flows (all values are given in ct/kWh)

	Case	1	2	3	P_{el}	4	5
$c_{E,j}$	***A***	**8.6**	**8.6**	**9.1**	**9.1**	**9.1**	**10**
$c_{E,j}$	***B***	**0.0**	**1.5**	**1.1**	**30.8**	**9.1**	**10**
$c_{Ex,j}$	*B*	-	22.7	30.8	30.8	55.0	55.8
$c_{An,j}$	*B*	0.0	0.0	0.0	0.0	0.0	0.0
$c_{E,j}$	***C***	**4.5**	**5.4**	**5.3**	**19.3**	**9.1**	**10**
$c_{Ex,j}$	*C*	-	17.8	19.3	19.3	24.3	26.0
$c_{An,j}$	*C*	4.5	4.5	4.8	-	6.1	6.5

3.4. Effect of the heat source temperature

An increasing temperature of the heat source leads to an increase of the exergy content of the supplied heat. This influences positively the entire process because the COP_{HP} depends on the temperature of the supplied heat.

Figure 7 shows the effect of an increase of temperature t_2, which directly influences the temperature of the heat supply of the heat pump t_3 (see section 3.1), on the specific energetic costs of the heat source. In the here considered temperature range the COP_{HP} increases from three to almost seven.

The different quality of the supplied heat is only visible in the costs for *case B* and *case C*. The specific costs increase significantly with the increasing temperature for both cases while the costs for *case C* are on a higher level. For *case B* the increase is more steep and approximate the

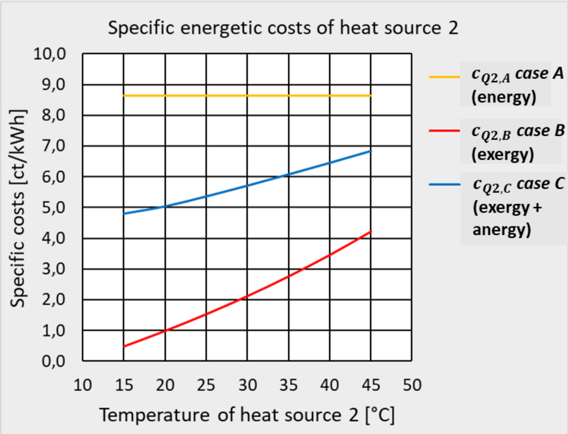

Figure 7 Effect of the heat source temperature on specific energetic costs

costs for *case C*. This is an indication that the consideration of the anergy might be less relevant for energy flows with relatively high exergy share. For the highest temperature $t_2 = 45°C$, the percentage of exergy in the heat flow is 13%.

3.5. Effect of the anergy-exergy cost ratio

It has been explained that the value for the ratio $r_{An/Ex} = 0.25$ is based on an assumption (see section 3.3). Therefore, it is revealing to study the dependency of the specific energetic costs on the ratio. In addition, this examination helps to understand that in fact a ratio $r_{An/Ex}$ is applied for all three approaches. For the energy-perspective, *case A*, and the exergy-perspective, *case B*, the ratios are: $r_{An/Ex\_A} = 1$ and $r_{An/Ex\_B} = 0$.

Figure 8 shows the specific energetic costs for the two heat sources and the electric power depending on $r_{An/Ex}$. The significance or the economic value of the exergy decreases with an increasing ratio and approaches a common value independently of the exergy share. For the analyzed system, a clear

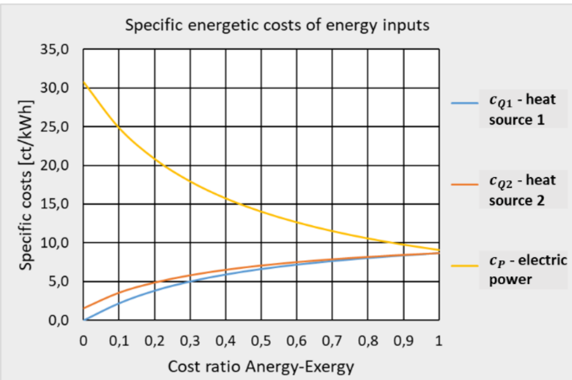

Figure 8 Effect of the anergy-exergy cost ratio on specific energetic costs

differentiation between the two heat sources is only possible for $r_{An/Ex\_B} < 0.5$, which is due to the relatively small difference in the exergy content of source 1 and 2.

The chart shows also that the ratio could be adapted to obtain certain specific costs for one of the energy flows. This might be interesting if e.g. the costs of the electric power supply of a system are a constraint within a project.

Case A and *case B* represent the outer limits where the specific costs are equal to the results shown above (see section 3.3). The application of a value for r_{An/Ex_B} in between one and zero (as realized for *case C*) allows deviating from these two extreme perspectives and from extreme economic evaluations of energy flows.

4. DISCUSSION AND CLOSURE

4.1. Conclusions

For an analysis of an exemplary heating system, it has been shown that the differentiation between exergy and anergy flows for allocating economic values is beneficial compared to approaches that allocate costs to energy or exergy only. The methodical concept allows to calculate meaningful acceptable costs for the energy inputs based on a fixed value for the heat generated by the system. In this way, the understanding of the cost formation throughout the process could be improved.

The novel approach seems to have advantages for processes where energy flows with low exergy content are used or generated and represent a certain economic value like in heating applications. For the analysis of e.g. power plants, the application probably does not generate any additional value compared to an exergoeconomic approach.

One central outcome of the investigation is that the definition of an anergy-exergy cost ratio makes the economic assessment of a process regarding the value of exergy and anergy very flexible. It allows adapting the evaluation to the (economic) constraints of the analyzed system.

It could be argued that the concrete figure of the value is defined somehow arbitrary. That is true, but this is also true, if the ratio is set equal to one as it is done implicitly for any energy-based analysis (*case A*). The equivalent consideration of exergy and anergy is misleading from an economic as well as from a thermodynamic point of view.

For an exergoeconomic approach (*case B*), the ratio is set to zero based on the fact, that from a thermodynamic perspective only exergy is useful (for performing work). For many energy conversion systems, the economic value is in accordance with the thermodynamic value. In fact, the new approach presented here, is proposed for systems where this is not the case and the anergy has an economic relevance.

4.2. Problematic aspects

As there are many methods used for thermo-economic analysis, it might be difficult to explain the differences of the new approach. The following aspects should help to clarify this:

- Anergy is not used as an economic or thermodynamic indicator itself. Together with exergy, it is the basis for allocating costs. The anergy is not meant to substitute any indicator as e.g. a primary energy factor or the exergy consumption of natural resources.

- The objective of the approach is not a more sophisticated thermodynamic analysis by calculating the (additional) thermodynamic property anergy, but to improve the allocation of costs in the system. The calculation of the thermodynamic properties should be done only as exact as necessary for this purpose.

- The allocation of costs or also environmental values or burdens to a flow (e.g. energy, exergy or material) through a process can be found not only in exergoeconomic analysis but also e.g. in exergoenvironmental analysis [9] material flow cost analysis (MFCA, EN ISO 14051) and life cycle assessment (LCA). The combination of the new approach with some of these methods seems to be promising.

Some challenges are linked to the application of the thermodynamic property anergy:

- In general, exergy approaches are well established in a scientific context of energy-engineering, but not widely-used in commercial engineering and probably rarely applied for interdisciplinary topics outside the academic world. There is a certain risk that by extension of exergy-based analysis with anergy it will be even more difficult to communicate and establish the approach for widespread use.

- The definition of exergy and its application in exergy-analysis is regularly part of thermodynamic textbooks for engineers. In German textbooks, the anergy is often defined in conjunction with exergy. This is probably due to the standard work of Baehr and Kabelac [2] and the early scientific work of Baehr in the field. As far as the authors have an overview, anergy is often not mentioned in popular English textbooks (e.g. [10]) or it is named “unavailable energy” [11]. Therefore, not surprisingly, the keyword anergy is only rarely found in scientific publications.

- The calculation of exergy and anergy has been explained in this paper in a simplified way, which is correct for the presented case study of a heating system, which is operated above ambient temperature but cannot be transferred easily to any other energy conversion process. E.g. for the application to a cooling system, the calculation becomes more complex. A discussion of the theoretical background for general exergy calculations can be found e.g. in [12].

4.3. Outlook

The approach presented in this paper seems to be beneficial for techno-economic analysis of thermal processes that include the consumption or generation of heat at relatively low temperatures. Possible real world applications are e.g.:

- District heating networks with heterogeneous heat producers and consumers

- Economic evaluation of waste heat sources and waste heat applications

- Steam networks with different steam quality levels

- Power to Heat systems that make use of low cost electric energy /exergy

In addition, the transfer of the methodical concept to environmental analysis could help to improve the results for the above-mentioned type of processes. An extension of environmental analysis by the application of the anergy-exergy ratio is possible e.g. for the exergoennvironmental method [9] and for the calculation of carbon footprints based on the allocation of CO_2 emissions to energy flows.

Accordingly, the next steps regarding the development of the methodical approach will be the application to a real process in combination with an exact thermodynamic and economic analysis and the investigation of the feasibility for environmental evaluations.

4.4. What about the apples?

Whenever we want to produce a mixture of apples and applesauce, we should analyze if it makes more sense to produce applesauce out of new entire apples or to make a source of already existing applesauce available. For a cost-efficient decision, we would definitely try to find out the price for all potential sources.

NOMENCLATURE

$\dot{An}$	Anergy flow / rate (kW)
$\dot{C}$	Cost flow / rate (ct/s)
c	Specific energetic costs (ct/kWh)
COP	Coefficient of performance
$\dot{E}$	Energy flow / rate (kW)
$\dot{Ex}$	Exergy flow / rate (kW)
P_{el}	Electric power (kW)
$r_{An/Ex}$	Anergy-exergy cost ratio
$\dot{Z}$	Component-related cost flow / rate (ct/s) associated with capital and O&M costs
Subscripts	
A	Case A
An	Anergetic
B	Case B
C	Case C
D	Destruction
E	Energetic
Ex	Exergetic
G	Generation
HN	Heat network
HP	Heat pump
in	Input
j	jth energy flow of the process
k	kth component of the process
L	Loss
out	Output
ST	Storage

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