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Teaching Exergy to Engineering Students in view of the Energy Transition

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Abstract:

In view of the energy transition, it is important that engineering students are familiar with the concept of exergy and the added value of exergy analysis compared to energy analysis. Exergy analysis tells the truth about energy efficiency and exergy is directly related to sustainable development. This paper focuses on teaching exergy to students at the Delft University of Technology (TU Delft), but the contents are valuable to other engineering students as well. To encourage the teaching of exergy, the basics of exergy and exergy analysis are presented, as well as examples and ideas for teaching exergy to BSc students that are related to the topics of their BSc programme. It is recommended that the contents of this paper be discussed with many teachers of BSc programmes, especially teachers of BSc programmes that do not yet seem to include the teaching of exergy, and that attention be paid to teaching exergy to MSc students as well.

Keywords:

Teaching; Exergy; Academia; Energy Transition; Added Value; Basics; Examples.

1. Added value of exergy

In view of the energy transition, it is of utmost importance that students graduating from technical universities are well aware of energy-related concepts such as heat, work, energy conservation and the work potential, or quality, of energy. This work potential is important since it is needed for all processes and activities to take place. Preferably, all students who become policy makers, whether they graduate from technical or from non-technical universities, are familiar with these concepts. The work potential of energy is known as exergy; a term proposed in 1953 by Z. Rant [1].

According to the Science Europe Physical, Chemical and Mathematical Sciences Committee, our society does not have an energy crisis, but an exergy crisis [2]. As they put it [2, p.2]: “It is, however, not energy per se that needs to be secure, affordable and sustainable but rather exergy.” and “Exergy analysis not only tells the truth about energy efficiency, but, in an extended perspective, potentially leads to resource accounting on a global scale: a common scale for our common future.”

Exergy analysis tells the truth about energy efficiency because it, in contrast with energy analysis, takes into account the work potential of the ingoing and outgoing flows of a process or system, and shows where work potential is lost. This loss of work potential cannot be made visible with energy analysis. Besides, the law of energy conservation tells that energy cannot be lost nor created. It can only change forms.

Knowing that work potential is needed for all processes and activities and that each process and activity is accompanied with the loss of work potential raises the question whether enough work potential is available to current and future generations. Sources of work potential are fossil fuels such as gas and oil, but these are not renewable and their use causes carbon dioxide emissions. An example of an infinite and renewable source of work potential is solar energy. Solar radiation is also essential for photosynthesis; for plants and trees to grow and to produce the substances necessary in living organisms. Like human processes and activities, photosynthesis and related natural processes involve loss of work potential as well.

Exergy analysis can be used to investigate the causes of the loss of work potential and whether there are possibilities to limit this loss, and thus limit the amount of work needed for the process or activity to take place. In this way, exergy analysis can also be helpful in the choice of which product(s) must preferably be produced,

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in the assessment of the reparability, reusability of products and the selection of, e.g., minerals that are used to produce a product.

The results of energy and exergy analyses may very well indicate different parts of processes or systems that have the largest room for improvement. For example, the results of an energy analysis of a methanol production process show that the distillation section needs improvement, while the results of an exergy analysis of the same process clearly indicate that the reforming section causes the highest exergy loss [3].

Furthermore, according to Dincer and Rosen [4, p.61]: “Many suggest that mitigating the environmental impact of energy resource utilization and achieving increased resource-utilization efficiency are best addressed by considering exergy. The relations between exergy and both energy and the environment make it clear that exergy is directly related to sustainable development.”

The calculation of exergy values of amounts of mass and/or energy is based on thermodynamic equations, which makes it a more fundamental method than other sustainability assessment methods because, e.g., the environmental impact is calculated by making use of models and weighting factors, the economic performance is based on costs that vary over time because of market developments, and the calculation of the societal impact of processes or systems is hampered by the limited availability and qualitative nature of data.

This paper focuses on teaching exergy to students at Delft University of Technology (TU Delft), Delft, Netherlands, because all authors have graduated from this university and are, or were, employed by this university. Chapter 2 considers the current status of exergy teaching at TU Delft. Chapter 3 deals with teaching exergy in general, while chapter 4 provides examples and ideas dedicated to students taking specific BSc programmes at TU Delft. This is followed by discussion, conclusions and recommendations.

2. Current exergy teaching at TU Delft

In the academic year 2022-2023, TU Delft offers 16 BSc programmes and more than 30 MSc programmes. The TU Delft study guide [5] was used to determine which of these programmes discusses exergy in one or more of their courses by searching the study guide for courses with the search text “exerg*”, thus with a wildcard at the end. This search resulted in the following eight programmes.

The BSc Mechanical Engineering includes the course Process Engineering & Thermodynamics (WB2543), with the ability to perform energy and exergy calculations of energy and process equipment being one of the learning objectives. The BSc Molecular Science & Technology comprises the course Energy, Recycling and Safety (4052ENRV6), where exergy is mentioned in the Dutch description (not in the English version) of the course contents as part of the topic energy, i.e. together with the energy balance of the earth, greenhouse effect and climate change. The BSc Systems Engineering, Policy Analysis & Management offers the course Processes in the Energy Sector (TB242EB), of which one of the learning objectives is dedicated to exergy, i.e. to be able to explain what exergy and exergy loss is and to calculate exergy losses, values and efficiencies. The BSc minor programme Engineering for Large-scale Energy Conversion and Storage (ELECS) comprises two courses that deal with exergy: the course Energy Conversion: Devices, Systems and Efficiencies (WB3575) applies exergy analysis to energy conversion systems, devices and processes and the course Assessment of Energy Systems (WB3585) applies several assessment methods, i.e. life cycle assessment and exergy analysis, to large scale energy conversion and storage systems. The MSc Applied Earth Sciences contains a course Energy Transition (AESM1315), of which exergy analysis belongs to the course contents, but in 2022/2023 only exam opportunities are offered because this course is discontinued. The MSc Architecture, Urbanism and Building Sciences offers the course User-centred Sustainability Studio (AR3B015), where exergy is mentioned in one of the titles listed as literature and study materials, i.e. Energy Potential Mapping - Visualising Energy Characteristics for the Exergetic Optimisation of the Built Environment [6]. The MSc Mechanical Engineering includes the course Equipment for Heat & Mass Transfer (ME45165), which deals with the principles of heat integration, exergy analysis and pinch technology for heat exchanger networks. The MSc Sustainable Energy Technology programme’s course The Necessity of Storage Technology (SET3080) investigates energy densities, efficiencies, capacities, exergies of thermal storage and combined heat and power possibilities.

This does not mean that teaching exergy is part of the aforementioned programmes only, since exergy could be taught in other programmes without mentioning it in the study guide. E.g. it is expected that the BSc Architecture, Urbanism and Building Sciences pays attention to exergy by means of the Exergy guidebook for building professionals [7]. Because of the strong relationship between exergy and thermodynamics, especially entropy (Section 3.1.1), the study guide was used to find programmes that contain courses in this field by using the search texts “thermodynamic*” and “entrop*”. This has been complemented with a search for courses dealing with “energ*” for BSc programmes which don’t seem to teach exergy, thermodynamics nor entropy. The reason for looking in more detail at the BSc programmes is that TU Delft offers 16 BSc programmes, while the number of MSc programmes is considerably larger, i.e. more than 30. This makes it more feasible to start with all BSc students being well aware of work potential, exergy, in view of the energy transition. Table 1 presents an overview of the results of the search for courses and programmes.

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Table 1. Overview of exergy and/or exergy related education per BSc and/or MSc programme according to the TU Delft study guide 2022-2023.

BSc programmes	**Exerg***	**Thermodynamic***	**Entrop***	**Energ***
Aerospace Engineering		x	x	
Applied Earth Sciences		x	x	
Applied Mathematics				x[1]
Applied Physics		x	x	
Architecture, Urbanism and Building Sciences				x[2]
Civil Engineering				x[3]
Clinical Technology		x		
Computers Science & Engineering				x[4]
Electrical Engineering				x[5]
Industrial Design Engineering				x[6]
Life Science & Technology		x	x	
Marine Technology		x		
Mechanical Engineering	x	x		
Molecular Science & Technology	x	x	x	
Nanobiology			x	
Systems Engineering, Policy analysis & Management	x	x		
MSc programmes	**Exerg***	**Thermodynamic***	**Entrop***	
Applied Earth Sciences	x	x		
Applied Mathematics			x	
Applied Physics		x		
Architecture, Urbanism and Building Sciences	x		x	
Chemical Engineering		x	x	
Civil Engineering		x		
Electrical Engineering			x	
Environmental Engineering		x		
Integrated Product Design		x		
Marine Technology		x	x	
Materials Science and Engineering		x	x	
Mechanical Engineering	x	x		
Sustainable Energy Technology	x	x		
Systems and Control			x	
Other	**Exerg***	**Thermodynamic***	**Entrop***	
Minor Engineering for Large-scale Energy Conversion and Storage	x			

[1] The course Mathematical Physical Models (AM3510) contains the derivation of differential equations from physical laws such as mass and energy conservation
[2] Several courses (codes with BK*) deal with energy use, in-house climate etc.
[3] Several courses (codes CTB*) deal with energy, e.g. energy balances, energy dissipation etc.
[4] The course Computer Organisation (CSE1400) deals with the design of digital computers and their energy use.
[5] E.g. the course Electrical Energy Conversion (EE2E11).
[6] The course Sustainable Impact (IOB3-5) considers the energy effectiveness in products, energy efficiency etc.

It can be concluded from the results in Table 1 that nine of the sixteen BSc programmes teach exergy and/or thermodynamics and that teaching entropy is part of the BSc Nanobiology. The other six BSc programmes do at least pay attention to energy, though it sometimes seems quite specific. Nevertheless, the contents of all BSc programmes provide starting points for teaching exergy.

3. Teaching exergy in general

General information about exergy can be found in literature (section 3.1). As an alternative, this chapter provides basic knowledge about thermodynamics (section 3.2), exergy calculations (section 3.3) and methods that apply exergy analysis (section 3.4).

3.1. Where to start?

Several textbooks about thermodynamics pay attention to exergy, e.g. the books by Moran and Shapiro [8], Smith, Van Ness and Abbott [9] and Cengel and Bowles [10]. Textbooks about exergy have been published as well, e.g. by Dincer & Rosen [4], Szargut, Morris & Steward [11], Kotas [12] and Sankaranarayanan, Van der Kooi and De Swaan Arons [13]. PhD theses may also be a valuable source of information, e.g. [3,14-16]. Many scientific papers about exergy have been published and even a journal dedicated to exergy analysis exists: the International Journal of Exergy [17]. More informal information can be found on websites such as

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the website ‘Do more with the quality of energy’, which explains in plain words, in Dutch, what exergy is [18] and the website tudelft.nl/exergy.

3.2. Basic thermodynamics

The concepts of energy, energy conservation, heat and work can in plain words be explained by an example from daily practice, such as the following example about bicycling. When someone wants to make a ride on their bike, they must exert a continued force on the pedals, in other words: they perform work. The larger the friction with the road, the larger the force that they need to exert on the pedals of the bicycle (be it by keeping the same speed, or by lowering the force and distance per revolution and making more revolutions). On the other hand, without friction, they would not start moving forward because the friction between the tires of the bicycle and the road is essential to start riding. Once started bicycling, it would be possible to bike at constant speed without using the pedals in case of a flat and frictionless road and the absence of any other friction effects. In reality, different types of friction occur and they must continue to exert a force on the pedals to continue biking, i.e. a continual work input is necessary. This work input is a form of energy. The law of energy conservation states that the total amount of energy remains the same. So, where does this work input go to? The exerted work causes deformation of the tires and road, and finally becomes heat at the temperature of the environment. Thus, the work input is transformed into other types of energy. This degradation of work is a general characteristic of processes that occur in reality.

The law of energy conservation is also known as the first law of thermodynamics. However, being more precise: the first law of thermodynamics results from applying the law of energy conservation to a system and its surroundings. Another important law of thermodynamics related to the concept of work is the second law of thermodynamics. This 2^{nd} law can be expressed as follows: in every real process degradation of work takes place, only in the limiting case of a reversible process the amount of work remains the same. In reality, reversible processes cannot take place because it is impossible to return both the system and the surroundings to the state before the process started. Examples of irreversibilities and driving forces are the following [7]: friction, heat transfer through a finite temperature difference, spontaneous chemical reactions and spontaneous mixing of substances with different compositions and unrestrained expansion of a gas or liquid to a lower pressure.

The transfer of energy between a system and its surroundings can be classified as work or as heat. The latter is caused by a temperature difference between the system and surroundings and always occurs in the direction of decreasing temperature. Examples of forms of energy that are different from work and heat are the following: kinetic energy, potential energy due to gravity, chemical potential energy, electrical energy etc.

3.3. Basic exergy calculations

This section is a selection of what 2^{nd} year BSc students Systems Engineering, Policy analysis & Management is taught about exergy analysis. After an introduction about the difference between energy and exergy and the added value of exergy, they learn how to calculate exergy values of mass and/or energy, which starts with the definition of exergy. Exergy is defined as the maximum theoretical amount of work that can be obtained when an amount of energy or mass is brought into total equilibrium with the reference environment. It follows from this definition that energy in the form of work resembles 100% exergy. The same holds for kinetic energy, potential energy due to gravity and electrical energy. To be able to calculate the maximum amount of work that can be obtained from other forms of energy, the reference environment needs to be defined. This reference environment is a model of the atmosphere, oceans and earth’s crust. It consists of components in total equilibrium with each other and at a certain pressure, p_0, and temperature, T_0, mostly 1 atm. and 25 °C, respectively. In some applications, e.g. in analyses related to the built environment, the actual pressure and temperature are used. The composition of the reference environment is chosen in such a way that by no means work can be obtained from the reference environment. A well-known and commonly used model of the reference environment has been developed by Szargut et al. [11].

3.3.1. Calculation of exergy values

The exergy value of heat is calculated from its energy value and the Carnot efficiency. Assuming a constant temperature of the heat, the exergy value of heat at a higher temperature than the temperature of the reference environment is calculated as shown in Eq. (1). N.B.: when temperature T is lower than T_0 the absolute value of the Carnot factor has to be used.

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$$Ex_{\mathrm{Q}} = Q \cdot \left(1 - \frac{T_0}{T}\right) \quad (1)$$

with:
Ex_{Q} = exergy value of heat [J]
Q = energy value of heat [J]
T = temperature of the heat (assumed constant) [K]
T_0 = temperature of the reference environment [K]

The exergy value of mass flows consists of a physical contribution, Eq. (2), a chemical contribution, Eq. (3) and/or a contribution due to mixing, Eq. (4), when the mass flow consists of more than one substance.

$$Ex_{\mathrm{m,phys}} = (H - H_0) - T_0(S - S_0) \quad (2)$$

with:
$Ex_{\mathrm{m,phys}}$ = physical exergy value of the substance [J]
H = enthalpy of the substance at its conditions [J]
H_0 = enthalpy of the substance at the pressure and temperature of the reference environment [J]
S = entropy of the substance at its conditions [J/K]
S_0 = entropy of the substance at the pressure and temperature of the reference environment [J/K]
T_0 = temperature of the reference environment [K]

$$ex^0_{\mathrm{ch},i}(T_0) = \sum(N_e ex^0_{\mathrm{ch},e}(T_0)) + \Delta_{\mathrm{f}} g^0_i(T_o) \quad (3)$$

with:
$ex^0_{\mathrm{ch},i}(T_0)$ = standard chemical exergy value of substance i at T_0 [J/mol]
$ex^0_{\mathrm{ch},e}(T_0)$ = standard chemical exergy value of element e at T_0 [J/mol]
$\Delta_{\mathrm{f}} g^0_i(T_o)$ = Gibbs energy of formation of substance i at T_0 [J/mol]
N_e = number of moles of element e per mole of substance i [-]

$$ex_{\mathrm{mixing}} = RT_0 \sum(x_i \ln(x_i)) \quad (4)$$

with:
ex_{mixing} = mixing contribution in case of ideal mixing [J/mol of mixture]
R = universal gas constant, 8.314 [J/mol·K]
T_0 = temperature of the reference environment [K]
x_i = molar fraction of substance i

3.3.2. Calculation and presentation of exergy losses and efficiencies

The loss of exergy can be subdivided into internal exergy loss and external exergy loss. The internal exergy loss, Eq. (5), is caused by irreversibilities (Section 3.2) and is also known as exergy destruction. The external exergy loss is the exergy that is lost with waste flows.

$$Ex_{\mathrm{loss,internal}} = \sum Ex_{\mathrm{in}} - \sum Ex_{\mathrm{out}} \quad (5)$$

Universal as well as functional exergy efficiencies of a system can be calculated. Where the universal exergy efficiency compares all ingoing and outgoing amounts of exergy, Eq. (6), the functional exergy efficiency takes into account the purpose of the system [19], e.g. the exchange of heat in a heat exchanger, Eq. (7).

$$\Psi_{\mathrm{univ}} = \frac{\sum Ex_{\mathrm{out}}}{\sum Ex_{\mathrm{in}}} \quad (6)$$

$$\Psi_{\mathrm{funct,heat\ exchanger}} = \frac{(Ex_{\mathrm{p,out}} - Ex_{\mathrm{p,in}})}{(Ex_{\mathrm{s,in}} - Ex_{\mathrm{s,out}})} \quad (7)$$

with:
Ex_{p} = exergy amount of the mass flow that is heated in the heat exchanger [J]
Ex_{s} = exergy amount of the mass flow that is cooled in the heat exchanger [J]

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Besides numerical representation of the results of exergy analyses, the loss of exergy can be shown in a Grassmann diagram, i.e. the exergy variant of the Sankey diagram, and/or in a value diagram. Originally, value diagrams were used for heat transfer processes, as they show the (1-T_0/T) value of heated and cooled flows versus the amount of heat that is transferred, but they can be used for the evaluation of thermal power plants as well [16].

3.4. Exergy methods

Scientists from all over the world have developed assessment methods that pay attention to exergy losses [3]. The following presents a brief overview of some important exergy analysis methods. The Cumulative Exergy Consumption (CExC) method was introduced in 1988 by Szargut et al. [11] and takes into account all exergy needed to produce a product, i.e. attention is paid to the exergy needed in its supply chains as well. A method that is considered equivalent [1] is the Exergetic Cost method developed by Valero et al. [20] in 1986. The CExC method was extended in 2001 with the abatement of emissions and the system itself by Dewulf et al. [21] resulting in the Cumulative Exergy Consumption for Construction and Abatement (CExCA) method. Around the same time, Sciubba [22] introduced the Extended Exergy Accounting (EEA) method which expands the CExC method by integrating thermo-economic methods and the inclusion of labour and environmental impact. The Cumulative Exergy Extraction form the Natural Environment (CEENE) method extends the CExC method with land use and was developed in 2007 by Dewulf et al. [23] to be used in combination with the ecoinvent database [24]. Examples of assessment methods related to the standard Life Cycle Assessment (LCA) method [25] are the following: Exergetic Life Cycle Analysis (ELCA) developed in 1997 by Cornelissen [26] includes the calculation of internal exergy losses, Life Cycle Exergy Analysis (LCEA) developed around the same time by Gong and Wall [27] calculates the exergetic pay-back time and the Exergoenvironmental analysis method introduced in 2009 by Meyer et al. [28] combines LCA with the Exergoeconomic analysis method by Tsatsaronis and Winhold [29]. This Exergoeconomic analysis method was introduced in 1984 for the combined exergetic and economic analysis of energy conversion processes and determines the costs of the exergy losses in the components of a system. The method was the basis of the Advanced exergoeconomic analysis method introduced in 2008, which splits the internal exergy losses into avoidable and unavoidable exergy losses and makes a distinction between exergy losses caused by the component itself and exergy losses caused by connected components [30]. The Total Cumulative Exergy Loss (TCExL) method can be regarded as combination of, or extension to, the CExC, CExCA, CEENE and ELCA methods and calculates all exergy losses caused by a technological system during its life cycle [3].

4. Examples and ideas for teaching exergy at TU Delft

The examples and ideas for teaching exergy presented in this chapter vary in difficulty, i.e. for students with no background in thermodynamics at all, for students with a background in thermodynamics but who are unfamiliar with exergy and some illustrative examples for students who have been taught how to carry out exergy analysis. Section 4.1 provides an overview of which examples/ideas are recommended for students from which BSc programme. Sections 4.2 to 4.8 introduce and explain these examples/ideas. Many more examples and applications of exergy analysis can be found in textbooks about exergy, e.g. [4].

4.1. Overview of examples/ideas and educational programmes

The results of the search for current education in the field of exergy, thermodynamic, entropy and/or energy presented in chapter 3 has been used as the starting point for providing examples/ideas for the teaching of exergy at TU Delft. The goal was to find examples/ideas that are related to the subjects the students are being taught during their BSc programme. The examples/ideas mentioned in Table 2 are based on examples used by the authors when teaching exergy to their students, complemented with examples that are expected to be interesting to students from other BSc programmes.

The authors recommend teachers to make the lectures interesting by interacting frequently with the students and to visualise the theory as much as possible, e.g. by visualising the difference between physical and chemical exergy or how the chemical exergy of a substance can be calculated from the standard exergy values of the elements. It is also recommended to alternate between explaining theory and letting the students make calculations based on the examples/ideas provided in this chapter during the lectures. The assessment can consist of theoretical questions about the concept of exergy as well as questions that require calculations by the students. The students may be expected to know the equations by heart before taking the exam, but another option would be to provide a formula sheet. In the latter case, it can still be tested whether the students understand the theory correctly, e.g. by providing a schematic overview of an energy system including the thermodynamic properties of the flows and asking the students to calculate the internal and external exergy losses, which implies that they e.g. need to understand which temperature and enthalpy and entropy values should be used for the calculation of the physical exergy of a mass flow.

Table 2. Overview of examples per BSc programme.

BSc programmes	Section(s)	Example(s)
Aerospace Engineering	4.7	Hydrogen combustion
Applied Earth Sciences	4.6	Heat exchanger
Applied Mathematics	4.2, 4.3.2	Energy/exergy, Electricity to heat
Applied Physics	4.6	Heat exchanger
Architecture, Urbanism and Building Sciences	4.2, 4.3.1, 4.6	Energy/exergy, Mixing hot/cold water, Heat exchanger
Civil Engineering	4.2, 4.3.1, 4.4, 4.6	Energy/exergy, Mixing hot/cold water, Iron production, Heat exchanger
Clinical Technology	4.2, 4.5	Photosynthesis
Computers Science & Engineering	4.2, 4.3.2	Energy/exergy, Electricity to heat
Electrical Engineering	4.2, 4.3.2	Energy/exergy, Electricity to heat
Industrial Design Engineering	4.2, 4.4	Energy/exergy, Iron production
Life Science & Technology	4.2, 4.5	Photosynthesis
Marine Technology	4.2, 4.4, 4.7	Iron production, Hydrogen combustion
Mechanical Engineering	4.6, 4.8	Heat exchanger, Heat pump
Molecular Science & Technology	4.7	Hydrogen combustion
Nanobiology	4.2, 4.5	Photosynthesis
Systems Engineering, Policy analysis & Management	4.2, 4.6, 4.7	Heat exchanger, Hydrogen combustion

4.2. Energy versus exergy

The teaching of exergy could start with the following example, which proved to be insightful to students who have never heard of exergy before (and maybe think the “x” is just a typo).

This example starts with telling that different types of energy exist and that one type of energy may be more valuable, or useful, than another type of energy. This could be followed by the teacher asking the students to mention some types of energy, i.e. electrical energy, heat, kinetic energy etc. Then the teacher tells the students that the valuable or useful part of energy has its own name: exergy.

After that, the teacher shows a sandwich, or a picture of a sandwich, and asks the students whether they know how many calories the sandwich provides and where these calories come from, i.e. from carbohydrates, proteins and oils/fats. Finally, the teacher tells the students that you could look at energy and exergy like the following: the energy represented by the sandwich are the calories and one of the components, e.g. the carbohydrates, is the exergy (although in reality all three components contain more or less exergy). So, exergy is a part of energy. The amount of exergy could be large or even 100%, i.e. many calories and many or all, in this case, carbohydrates such as with a sugar cube. And the amount of exergy could be small or even zero, i.e. calories without these carbohydrates such as with a piece of fish.

4.3. Energy conservation versus exergy loss

4.3.1. Mixing of hot and cold water

The difference between energy and exergy analysis can easily be shown with the following example about the mixing of hot and cold water. The example is about filling a bath tub, but of course the teacher can think of another situation that is applicable.

An empty and well-isolated bath tub is filled with two buckets of hot water of 60 °C and two buckets of cold water of 20 °C, resulting in warm bath water with a temperature of 40 °C, i.e. there are no heat losses from the hot or warm water to the bathroom. The temperature in the bathroom equals 20 °C. Table 3 presents an overview of the energy and exergy values of the water in the buckets.

Table 3. Energy and exergy values of buckets filled with water.

Water temperature [°C]	Energy [kJ/bucket]	Exergy [kJ/bucket]
60 °C (hot)	2511	105
20 °C (cold)	839	0
40 °C (warm)	1675	28

The question to be asked to the students would be: calculate the total amounts of energy and exergy before the mixing of water and after the mixing of the water, and compare the results. The answer is quite straightforward since the total amount of energy before mixing equals 2*2511+2*839 = 6700 kJ, which is the same as the amount of energy after mixing, i.e. 4*1675 = 6700 kJ. In case of exergy, these values are different, i.e. 2*105+2*0 = 210 kJ before mixing and only 4*28 = 112 kJ after mixing. With this example, the teacher can let the students experience that the total amount of energy stays the same, is conserved, but that this does

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not hold for the total amount of exergy. The mixing of hot and cold water causes exergy loss. This exergy loss is of the type internal exergy loss, also known as exergy destruction, and the driving force that causes this exergy loss is the difference in temperature between the hot and cold water (Section 3.2).

4.3.2. From electricity to heat

The following example is about a laptop, but it is applicable to many more electrical devices, such as an electrical heater, a television, a vacuum cleaner etc. The only thing is that the power of the device and the temperature of the emitted heat will be different.

Assume that a laptop is used to write a conference paper about teaching exergy, that the power of this laptop equals 50 W and that the room in which the author writes their paper has a constant temperature of 18 °C. The laptop gets warm during the writing of the paper and constantly emits heat of 60 °C.

The question to be asked to the students would be: perform an energy and exergy analysis of this warm laptop. The answer to the first part of the question is, again, quite straightforward since the power consumed by the laptop will be fully converted into heat, i.e. the heat generation equals the electric power and both equal 50 W. The results of the exergy analysis are, again, different, since electric power represents 100% exergy, while the exergy content of heat depends on the temperature of the heat and the temperature of the reference environment (Section 3.3.1), in this case the temperature of the room since no other information is available. The amount of heat represents an exergy amount of (1-(18+273.15)/(60+273.15))*50 = 0.13*50 = 6.3 W. Thus, the internal exergy loss equals 50-6.3 = 44 W, i.e. 87% of the exergy input, which is very different from the 0% loss according to the energy analysis.

4.4. Iron production

The usual way of producing iron, e.g. to be used in parts of a bicycle or for large constructions, is the blast furnace process, which converts iron ore into pure iron by burning coke (carbon) and results in the emission of carbon dioxide, Eq. (R1). The reactants are at 298 K and the products at 1809 K.

$$\mathrm{Fe_2O_3(s) + 5.7C(s) + 4.2O_2(g) + 17N_2(g) \rightarrow 2Fe(l) + 5.7CO_2(g) + 17N_2(g)} \quad \text{(R1)}$$

In view of the energy transition, attention is paid to an alternative way of producing iron, i.e. with hydrogen instead of coke, Eq. (R2).

$$\mathrm{Fe_2O_3(s) + 8.1H_2(g) + 2.5O_2(g) + 10N_2(g) \rightarrow 2Fe(l) + 8.1H_2O(g) + 10N_2(g)} \quad \text{(R2)}$$

Table 4 provides the exergy values of the reactants and products of Eqs. (R1) and (R2). The question to be asked to the students would be: calculate the total exergy input of the original blast furnace process and the alternative process with hydrogen, the percentage of exergy that is lost and compare the results with regard to exergy and emitted components.

Table 4. Chemical exergy values of the substances of Eqs. (R1) and (R2) [31,32].

Reactants at 298 K	Exergy [kJ/mol]	Products at 1809 K	Exergy [kJ/mol]
Fe_2O_3(s)	12.4	Fe(l)	415
C(s)	411	CO_2(g)	73
O_2(g)	3.97	H_2O(g)	51
N_2(g)	0.72	N_2(g)	33
H_2(g)	236		

The exergy inputs of the original and alternative processes equal 2384 kJ/mol iron ore and 1941 kJ/mol iron ore, resp., and are obtained by multiplying the exergy values of the components with the stoichiometric coefficients shown in the reaction equation. The total exergy of the products is calculated analogously and comparing the exergy input with the exergy output results in exergy losses of 24% and 19%, respectively.

4.5. Photosynthesis

Each and every process is accompanied with exergy losses: technological processes as well as natural, biological processes such as photosynthesis. In his PhD thesis [14], Lems provides a detailed exergy analysis of photosynthesis. He assesses the light and dark reactions of photosynthesis separately and combines them into the following overall reaction equation, Eq. (R3):

$$\mathrm{6CO_2 + 6H_2O + 6P + 24h\nu_{680nm} + 24h\nu_{700nm} \rightarrow 6C_6H_{12}O_6 + 6O_2 + 6P_{ATP}} \quad \text{(R3)}$$

with:

$h\nu_{680nm}$ and $h\nu_{700nm}$ = photons with a wavelength of 680 nm and 700 nm, respectively

P = inorganic phosphate

P_{ATP} = terminal phosphate group of ATP (adenosine triphosphate)

Table 5 shows the exergy values of the substances. The exergy value of photons can be calculated in the same way as the exergy value of heat, i.e. from the energy value of the photons times the Carnot factor, with T_{low} and T_{high} being the surface temperatures of the earth (298.15 K) and the sun (5762 K), respectively. The Planck constant equals 6.626×10^{-34} Js.

Table 5. Exergy values of the substances occurring in the overall photosynthesis reaction.

Substance	Exergy [kJ/mol]	Comment [14]
$C_6H_{12}O_6$ (glucose)	2955	
CO_2	≈ 0	almost in equilibrium with the concentration in the atmosphere
H_2O	0	taken at zero
O_2	≈ 0	considered to be in equilibrium with air
P_{ATP}	306	compared to P

The question to be asked to the students would be: calculate the exergy loss caused by the overall photosynthesis reaction.

The answer can be calculated as follows. The exergy value of one mole of photons with a wavelength of 680 and 700 nm equals $6.26 \times 10^{-34} * (3.0 \times 10^{8} / 680 \times 10^{-9}) * (1 - 298.15/5762) * 6.022 \times 10^{23}$ = 162 kJ and, analogously, 167 kJ, respectively. This results in a total exergy input of 24*162 + 24*167 = 7896 kJ. The total exergy output equals 2955 + 6*306 = 3261 kJ. Combining these answers results in an exergy loss of 7896 - 3261 = 4635 kJ per mole of glucose formation.

4.6. Energy and exergy analysis of a heat exchanger

An interesting example of the differences between energy and exergy analysis and between universal and functional efficiencies (Section 3.3.2) is the assessment of an ideal counter current heat exchanger. Table 6 shows the enthalpy (i.e. energy) and entropy values of the primary and secondary flows, i.e. steam and flue gas, respectively. The steam is heated from 138 to 234 °C, the flue gas cooled from 436 to 220 °C and the temperature of the reference environment equals 15 °C. The chemical exergy value of flue gas equals 69 kJ/kg.

Table 6. Enthalpy and entropy values of flue gas (41 kg/s) and steam (29 kg/s).

Substance	h_{in} [MJ/kg]	h_{out} [MJ/kg]	h_0 [MJ/kg]	s_{in} [kJ/kg·K]	s_{out} [kJ/kg·K]	s_0 [kJ/kg·K]
Flue gas	-3.5	-3.8	-4.3	7.9	7.5	6.0
Steam	0.58	1.0	0.063	1.7	2.6	0.22

The question to be asked to the students would be: calculate and compare the universal and functional energy and exergy efficiencies of the heat exchanger. Table 7 shows the results obtained by using the enthalpy values of the in- and outgoing flows to calculate the energy flows, Eq. (2) to calculate the exergy flows and Eqs. (6) and (7) for the calculation of the universal and functional efficiencies. The differences between the energy and exergy efficiencies as well as between the universal and functional exergy efficiencies are remarkable.

Table 7. Universal and functional energy and exergy efficiencies of the heat exchanger.

	Universal [%]	Functional [%]
Energy	100	99
Exergy	82	62

4.7. Hydrogen combustion

One of the energy carriers that has gained interest in view of the energy transition is hydrogen, since it can be produced when there is an excess of wind energy, stored, and combusted in a power plant when there is a shortage of electricity from renewable energy sources, although the round-trip efficiency is low.

The following example is about calculating the exergy loss during hydrogen combustion with pure oxygen. It is assumed that the combustion temperature equals 1100 °C. The temperature of the reference environment is set at 25 °C and the Gibbs energy of formation of water at 25 °C equals -237 kJ/mol. Table 8 shows the other thermodynamic data needed for this example.

Table 8. Exergy values of the substances related to hydrogen combustion, at 1 atm [31].

Substance	Enthalpy at 1100 °C [kJ/mol]	Enthalpy at 25 °C [kJ/mol]	Entropy at 1100 °C [J/mol·K]	Entropy at 25 °C [J/mol·K]	Standard chemical exergy [kJ/mol]
H_2 (hydrogen)	32	0	176	131	236
O_2 (oxygen)	36	0	255	205	3.97
H_2O (water)	-200	-286	246	70	to be calculated

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The question to be asked to the students would be: calculate the exergy loss caused by the combustion of hydrogen when the effect of mixing is neglected. The solution to this example consists of the following steps: 1) calculate the physical exergy values of the reactants (H_2, O_2) and product (H_2O) with Eq. (2), 2) calculate the chemical exergy value of H_2O with Eq. (3), 3) calculate the total exergy value of the reactants and product, 4) calculate the amount of heat that is released during combustion and calculate its exergy value with Eq. (1), 5) calculate the exergy loss by subtracting the total amount of exergy out from the total amount of exergy in. Table 9 shows the results.

Table 9. Results of the example about hydrogen combustion.

	Energy [kJ/mol H_2]	Physical exergy [kJ/mol]	Chemical exergy [kJ/mol]	Total exergy [kJ/mol]	Total exergy [kJ/mol H_2]	**Total**
IN						**268**
H_2		19	236	255	255	
O_2		21	3.97	25	13	
OUT						**203**
H_2O		34	0.99	35	35	
Heat of combustion	214			168	168	
Exergy loss						**65**

4.8. Energy and exergy analysis of a heat pump

The implementation of electric heat pumps in industry and households is very relevant in view of the energy transition. In this example, operational costs are allocated to the exergy destruction in the heat pump components. Assume that the heat pump operates 8.000 hrs per year, during 5 years at an electricity price of 0.041 €/kWh. The efficiency of the compressor drive, η_m, equals 85%. The temperature of the reference environment is set at 20 °C. Table 10 shows the mass flows and thermodynamic data of the flows.

Table 10. Mass flows and thermodynamic data needed for the heat pump example.

Component[1]	Working medium (2.1 kg/s)		Source or Sink (30 kg/s)			
	h_{in} [kJ/kg]	s_{in} [J/kg·K]	h_{in} [kJ/kg]	s_{in} [J/kg·K]	h_{out} [kJ/kg]	s_{out} [J/kg·K]
Evaporator	322	1,421	126	437	108	378
Compressor	581	2,305	n/a	n/a	n/a	n/a
Drive	n/a	n/a	n/a	n/a	n/a	n/a
Condenser	626	2,347	168	572	189	639
Expansion valve	322	1,406	n/a	n/a	n/a	n/a

[1] The working medium leaving the evaporator has the conditions of the working medium entering the compressor, etc.

The question to be asked to the students would be: calculate per component the amount of energy transferred, the exergy destruction and the related operational losses (costs). Table 11 presents the results, which have been calculated as follows. The energy transfer by the evaporator, compressor, condenser and expansion valve follows from the difference in enthalpy of the ingoing and outgoing working medium. The energy transfer by the drive has been calculated with $W_D = W_C/\eta_m$. The exergy destruction caused by the evaporator, compressor, condenser and expansion valve has been calculated with Eqs. (2) and (5), where H_0 and S_0 cancel out. The exergy destruction caused by the drive is taken as the difference with the compressor duty, i.e. W_D minus W_C. The operational losses are calculated by multiplying the exergy destruction with the number of operating hours per 5 years and the costs per kWh.

Table 11. Results of the heat pump example.

Component	Energy transfer [kW]	Exergy destruction [kW]	Operational losses [k€]
Evaporator	544	21	35
Compressor	95	26	42
Drive	111	16	27
Condenser	638	18	30
Expansion valve	0	9	15

5. Discussion and conclusions

It is said that our society does not have an energy crisis, but an exergy crisis, and that exergy is directly related to sustainable development. Despite the added value of exergy analysis compared to energy analysis, it is important to pay attention to all three pillars of sustainability, i.e. to the environmental, economic as well as the social sustainability of processes and activities.

The reader of this paper may get the impression that exergy losses should be avoided by all means, but the loss of exergy is unavoidable; it is needed to overcome friction and to achieve a reasonable speed of processes and activities. However, too large driving forces, e.g. differences in pressure and/or temperature, should be avoided because this would lead to a too large input of work.

Although exergy analysis, paying attention to the loss of work potential, is relevant in view of the energy transition, it seems that teaching exergy is not common practice at TU Delft. It was learnt from the TU Delft study guide that probably just 4 of the 16 BSc programmes, 1 BSc minor programme and 4 of the more than 30 MSc programmes pay attention to exergy and exergy analysis. However, a more detailed investigation is needed before firm conclusions can be drawn about the extent to which teaching exergy is part of the TU Delft educational programmes.

The basics of thermodynamics and exergy calculations presented in this paper are meant as a first step in teaching exergy in academia, but it cannot be ruled out that (essential) information is missing. The same holds for the brief overview of exergy methods.

The authors like to emphasize that the understanding of the exergy concept is highly valuable for both engineering professionals and policy makers that have to decide about the energy transition. Exergy analysis provides a more thorough understanding of the improvement potential of processes and systems. It helps to better understand how to reach sustainability goals such as the reduction of carbon dioxide emissions and improving resource efficiency.

6. Recommendations

It is recommended that a more detailed investigation of the teaching of exergy at TU Delft be carried out and that the contents of this paper be discussed with many teachers of BSc programmes, especially teachers of BSc programmes that do not yet seem to include the teaching of exergy. Based on these discussions, dedicated examples and ideas can be developed for teaching exergy as part of BSc programmes. It is recommended that attention be paid to teaching exergy to MSc students as well.

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