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Energy Value and Pricing

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Energy is only of value insofar it can be converted from one form to another. The conversions of energy from one accumulated state to other yield transient forms of energy, which are used for technical purposes. For instance, the kinetic energy of a system can be used to lift a weight. The energy of a motion system, accumulated in the kinetic form, is thereby converted to potential accumulated energy of an elevated weight, yielding a special temporary form of energy: mechanical work. Mechanical work is an especially valuable form of energy. The other valuable form of energy is the energy of electrical current, i.e. the electrical energy. Upon transfer of internal energy from one system to another, driven by a temperature difference, heat emerges as the transient energy. Heat is exploited for technical purposes as well. It has been known for a long time that energy can be transformed from one form to another, and it is also well known its convertibility is not unlimited: some forms of energy can be fully converted to other forms and some forms of energy are only convertible to other forms to a limited extent. For example, every form of energy can be fully converted to internal energy, but there are certain limitations to the conversion of internal energy to mechanical work.

Obviously, the types of energy convertible to other forms without limitations are worth more than those with limited convertibility or the types which are not convertible at all. Curiously enough, our awareness of different values of energy in their use is low and the differences are not taken into account for the purposes of billing at all. It is high time to clarify the concepts in this important field.

Mechanical work and electrical energy as its equivalent are the most useful types of energy.

A type of energy can therefore be valued by its convertibility to (mechanical) work. While the majority of known energies can be transformed to work in full extent, this is not possible for heat or internal energy.

In order to acquire work from heat, received from a heat source at temperature T_t, a part of the heat has to be rejected to a body or system at a temperature lower than T_t. Maximum work is obtained from a given quantity of heat if the whole process is run reversibly and the heat is rejected to a system at the lowest temperature available. The lowest temperature available for these purposes is the environment temperature T_0. Maximum work that can be obtained from heat Q is therefore:

$$A_{max} = Q\left(T_t - T_0\right) : T_t \qquad (1)$$

The fraction $\left(T_t - T_0\right) : T_t$ is often referred to as the Carnot efficiency. The amount of energy rejected from the process to the environment is:

$$Q_0 = Q\left(T_0 : T_t\right)$$

This energy has no value whatsoever, just the same as the internal energy of the environment has no value. Consequently, we cannot talk about energy *loss* in this case. Something that has no value cannot be lost.

Substances that carry energy are processed in technical devices, i.e. machines or factories. The schematic for this procedure is shown in Figure 1. The device can be completely arbitrary, e.g. a single turbo generator, or a whole thermal power plant with its boilers, machinery and so forth. It is not even necessary that it is designed to generate work or electrical power, it may be a chemical apparatus, a chemical factory etc. A substance at state 1 (p_1, T_1, V_1 …) enters the device, where it is processed to finally exit at state 2 (p_2, T_2, V_2 …). The work acquired in the process is A. Maximum work is acquired if the process is fully reversible and if the exiting

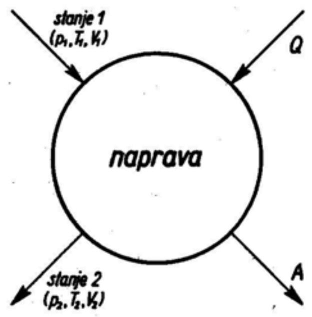


Figure 1: (naprava – device; stanje – state)

substance is in equilibrium with the state of environment ($p_2 = p_0$, $T_2 = T_0$). Considering the fact that all reversible processes between two given states are energetically equivalent, any reversible process may be selected for our calculations; naturally we shall pick the simplest one.

An isentropic (adiabatic) expansion equalizes the temperature of the substance with the environment temperature T_0, whereas the entropy of the substance remains unchanged. This is followed by an isothermal expansion to environment pressure p_0, whereas heat Q is supplied from the environment. The entropy of the substance increases from S_1 to S_2.

Let us introduce the energy balance for the device:

Input: internal energy of the substance U_1
work to feed the substance p_1V_1
heat $Q = T_0 (S_2 - S_1)$

Output: internal energy of the substance U_2
work to remove the substance p_0V_2
produced work A_{max},

therefore $U_1 + p_1V_1 + T_0 (S_2 - S_1) = U_2 + p_oV_2 + A_{max}$

Taking into account the relation

$$U + pV = I \text{ (enthalpy)}$$

and rearranging, the relation first derived by BOŠNJAKOVIĆ is obtained:

$$A_{max} = I_1 - I_2 - T_0 \left(S_1 - S_2\right) \quad (2)$$

Let us repeat that I_2 and S_2 are the enthalpy and the entropy of the substance at environment temperature and pressure.

The maximum work obtainable from a given quantity of energy is by all means a very important and remarkable property that deserves its own name. The word "energy" is derived from two Greek words: έν = inside and ἔργον = work, meaning the "work" hidden "inside" a system. The name for the work obtainable "from" (in Greek: έχ or έξ) this system can therefore be composed as **"exergy"**. The maximum work obtainable from energy shall be referred to as **exergy *E***. Every ***energy*** contains given ***exergy***. Exergy is the part of energy having value. Energy without exergy is valueless.

Equations are available to determine the exergy for different forms of energy:

for heat Q at temperature T_t:

$$E_Q = Q \left(T_t - T_0\right) : T_t \quad (3)$$

for energy, carried by a substance (matter):

$$E_M = I_1 - I_2 - T_0 \left(S_1 - S_2\right) \quad (4)$$

For all the other known forms energy, e. g. kinetic, potential and electrical energy, exergy is equal to the energy itself. Although quite improbable, we cannot exclude the existence of some other, not yet discovered forms of energy, for which the exergy may have to be determined using some different equations.

It is evident from the equations above that the exergy of heat at environment temperature is zero. Likewise, the exergy of a substance or system is zero when the system is in equilibrium with the environment.

The units of exergy are the same as the units of energy (J, kcal, kWh…). However, exergy differs significantly from energy in that the sum of exergies

in a closed system is not constant. Every irreversible process reduces the system's exergy. It follows that exergy is not "indestructible" like energy. On the contrary: we must treat it with special care and sensibly, so as to preserve it. The most important task of an energy engineer is to waste as little exergy as possible, for any loss of exergy is final and irreparable.

It was easy to convince ourselves of the significance of exergy at obtaining work. Still, is exergy really a universal measure of energy value? There are countless cases not involving work, where the energy is used for heating, in chemical, metallurgical and other processes. In these cases it is not our goal to convert heat or internal energy to work. At first it may seem that a calorie obtained from a heat source is equal to a calorie supplied to a heated system. Consequently, there is no apparent need to evaluate energy by its exergy. As it will be shown below, such reasoning is wrong.

A system, let us say a heated room, requires a given quantity of heat (Q_k) at temperature T_k (Fig. 2). This heat is represented in the *T*-*s* diagram by the area of rectangle (1, 2, 3, and 4).

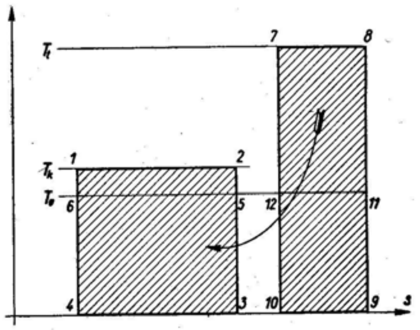


Figure 2

The heat is available at temperature T_t (e.g. the average temperature of flue gases in a furnace) and the environment temperature is T_0. The simplest method of heating involves direct removal of heat from a heat source and its transfer to a heat consumer. In this way, the amount of thermal energy Q_t removed from the source at temperature T_t equals the amount of heat supplied to the heated system:

$$Q_t = Q_k$$

In Figure 2, Q_t is represented by the area □ (7, 8, 9, 10), which is obviously equal to the area □ (1, 2, 3, and 4). There are no losses as far as energy is concerned.

What about the exergies? The exergy of heat Q_t is $E_t = Q_t\,(T_t - T_0) : T_t$, equal to area □ (7, 8, 11, 12); the exergy of thermal energy Q_k used for heating is $E_k = Q_k\,(T_k - T_0) : T_k$; E_k = □ (1, 2, 5, 6); considering $Q_k = Q_t$ and $T_k < T_t$, we can also establish that $E_k < E_t$. The exergy has been reduced in this process. The cause for the loss of exergy is the irreversible transfer of heat from the source to the system at a limited and, usually, quite large temperature differences $T_t - T_k$. Wherever irreversibility's are present, things are not in order energetically, even if it seems otherwise. The method of heating can be improved significantly as follows (Fig. 3):

Only as much heat Q_t' is removed from the source at temperature T_t, so that its exergy E_t equals the exergy E_k of thermal energy Q_k used for heating. We get:

$$Q_t' = Q_k \frac{T_k - T_0}{T_k} \cdot \frac{T_t}{T_t - T_0} \tag{5}$$

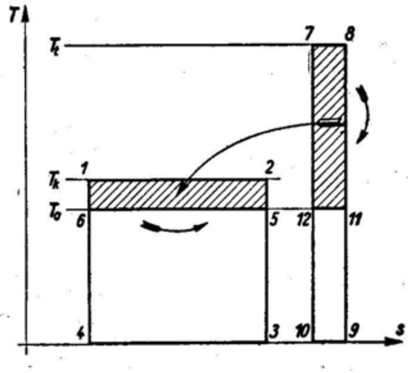


Figure 3

Taking into account $(T_k - T_0) : T_k < (T_k - T_0) : T_t$ we obtain $Q_t' < Q_k$. The areas in Figure 3 are:

Q_k = □ (1, 2, 3, 4), E_k = □ (1, 2, 5, 6),
Q_t' = □ (7, 8, 9, 10), E_t' = □ (7, 8, 11, 12),
$E_k = E_t'$

The exergy E_t' coming from the source of removed heat Q_t' is converted to work using a power cycle, and this work is then used to drive a reversed (anti-clockwise) Carnot cycle (1, 6, 5, and 2). Valueless heat □ (6, 5, 3, and 4) is removed from the environment in this process; this heat has no exergy. The heated system is provided with heat Q_k = □ (1, 2, 3, 4) having the necessary exergy E_k = □ (1, 2, 5, 6). This method of heating removes less energy from the heat source than required for heating; but the exergy removed from the heat source equals the spent exergy.

This is the operating principle of a heat pump.

Hence it follows that energy containing exergy is required for heating and similar processes, too. Energy without exergy is not usable. The exergy for heating can be removed from an arbitrary source and in arbitrary form, e.g. as electrical energy from a hydroelectric power plant, from a power cycle operating between temperatures T_t and T_o etc.

Using this exergy, as much worthless internal energy is supplied from the environment as is needed for heating, and elevated to an appropriate temperature T_k. Exergy is used to enrich this worthless energy.

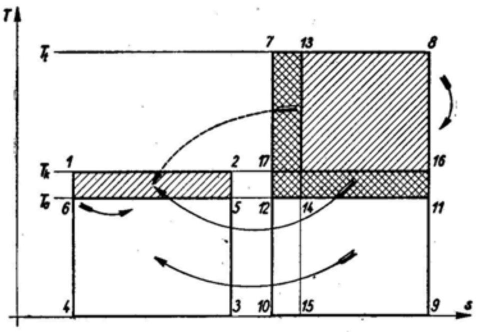
Exergy is the measure of energy's value for heating and similar processes, too.

Let us take a look at another example (Fig. 4)!

(1, 2, 3, 4) is our well-known heating process. In addition to it, a power cycle (7, 8, 9, and 10) is operating between the temperatures T_t and T_o. The width of this power cycle equals the width of the heating process:

$$S_9 - S_{10} = S_3 - S_4$$

The power cycle removes energy from the heat source equal to area □ (7, 8, 9, and 10) and containing the exergy □ (7, 8, 11, and 12). Energy □ (12, 11, 9, 10) having no exergy is removed from the process. A part of this process' exergy will be used for the heating process, as explained in the previous example, and the remaining exergy is free at our disposal. Analogous to Figure 3, exergy □ (7, 13, 14,



Sl. 4.

Figure 4

and 12) shall be used to drive a heating process (heat pump). The remaining exergy is equal to area □ (13, 8, 11, and 14). We are not obliged to use exactly the said part of the power cycle's exergy for the heating process; any arbitrary part of the rectangle □ (7, 8, 11, 12) will do the same work, provided its area is equal to □ (1, 2, 5, 6). Therefore we can also take the exergy represented by the rectangle □ (17, 16, 11, and 12). The exergy left for the other needs then equals □ (7, 8, 16, 17) = □ (13, 8, 11, 14). The exergy used for the heating process □ (17, 16, 11, and 12) takes the same position in the diagram as the exergy of thermal energy used for heating □ (1, 2, 5, and 6) – the temperatures and entropy differences are the same. The energy rejected by the power cycle to the environment □ (12, 11, 9, and 10) equals the energy, removed by the heating process from the environment □ (6, 5, 3, and 4). Both energies have no exergy.

The power cycle and the heating process can also be combined more closely:

The exergy-less heat □ (12, 11, 9, 10), which would otherwise have to be rejected from the power cycle to the environment, is surrendered directly to the heating process. In this way, the heating process is supplied with the exergy-less energy from the power cycle, no longer drawing it from the environment. The heating process only has to elevate this heat to heating temperature T_k with a heat pump. Inside the heat pump, exergy □

(1, 2, 5, 6) is added to the heat □ (12, 11, 9, 10) = □ (6, 5, 3, 4), its quantity and position being equal to the exergy from the power cycle □ (17, 16, 11, 12).

We have to ask ourselves whether it is necessary at all to convert the exergy □ (17, 16, 11, and 12) to work and use it to drive a heat pump. We could simply leave this exergy with heat □ (12, 11, 9, 10), which is rejected from the power cycle, only to have the said exergy added to it later. The heating process can be operated directly using the energy □ (12, 11, 9, 10) + □ (17, 16, 11, 12) = □ (17, 16, 9, 10) = □ (1, 2, 3, 4). In this case, the bypass over a heat pump is no longer necessary.

Two energy transformations are avoided in this manner: obtaining work from the process (17, 16, 11, 12) and supplying work to the process (1, 6, 5, 2) using a heat pump.

This leads us to a combined process that produces work or electrical energy, as well as the energy for heating. The energy □ (7, 8, 9, 10) containing the exergy □ (7, 8, 11, 12) enters the process. The exergy □ (7, 8, 16, and 17) is used to produce work and the exergy □ (16, 11, 12, and 17) is used for heating.

Such a process is used in heat engines, where steam at high inlet pressure and temperature is used to produce the electrical energy and steam at low pressure and temperature is used for the heating.

A condensing steam device uses all of the steam's exergy to produce electrical energy; while in a combined device the difference of exergies in entering and exiting steam is used for the electrical energy, and the exergy of exiting steam is used for the heating. Since the efficiencies of condensing and back-pressure turbo generators do not differ significantly, the quality of transformation of steam's exergy into electrical energy is approximately the same for both types of machines: the ratio of spent exergy to produced electrical energy is practically the same. *The common notion that cogeneration of electrical power and heat improves the production of electrical power is therefore erroneous.*

On the other hand, the conditions for heating improve significantly. While direct heating (Fig. 2) is burdened with large losses due to irreversibility's, as evidenced by the overuse of exergy, a combined process is in this respect equivalent to heating with a heat pump (Fig. 3), where all the irreversibility's are avoidable in theory. Practically, a combined process still has a large advantage compared to a heat pump: the heating part involves no transformations of energy and therefore no additional machinery or related inherent losses.

Taking everything into account, the following unavoidable conclusions have to be drawn regarding the energy pricing (accounting):

The existing method for energy pricing (accounting) in combined plants on the basis of used enthalpies is fundamentally wrong. It has to replace with pricing (accounting) on the basis of used exergies, which is the only proper way. Consequentially, the price of electrical power will increase and the price of heat will fall, both in accordance with the value of these two energies.

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