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WHAT IS EXERGY ?

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To whom it might concern

-What is Matter ?
-Never mind.
-But what is Mind ?
-It doesn't matter
(From a talk of a curious boy and his grandfather).

When I went to school, rather long ago, I learned at the Physics lessons about mass, force, work, energy, charge and other important things. But I never heard the word "exergy".

Now, when I am writing these lines, I keep in mind our children and grandchildren. I wish to do my best to tell them and other teenagers and, perhaps, their teachers, what exergy is, in order to include it in the list of the above mentioned terms.

I realize, that to tell on fundamental physical terms in the form of their definition, using other, more understandable words is almost impossible. There are no such words, more simple, than mass or energy. Examples, taken from everyday experience or seen in the nature or engineering might help to understand "what it is". I'm sure, that the term "exergy" should be brought just to teenagers, irrelevant to their future profession. Otherwise their education would be incomplete. Exergy will help to form the weltanschauung of young people toward sustainable world development

Natural questions

Something is rotten in the state of Denmark.
(Shakespeare, Hamlet)

Something is really not in order ("rotten") in the fundamental definitions.
One may find such a wording in many textbooks for schoolchildren: *Energy is the ability to do work.* If one is so curious as to search what work is , he finds the answer : *Work is energy in transition…* or about the same, *…energy transfer across a boundary.* Such a couple of definitions form the vicious circle. The history of Physics shows, vicious circles occur to cover a misunderstanding.

Other questions appear, when a pupil learns the energy conservation Law from a teacher. " I have heard many a times we are obliged to save energy, to prevent its wasting because it is very difficult to produce it. Why I need to conserve energy if our Lord actually does this? Would he like to do the same in the future as he did it in the past ? And how is it possible to produce energy if it can't appear or disappear ? I feel, I need to conserve something, but what it is ?"

These questions are not naive. They, however, are missing in the schoolyears Physics. I'm trying here to fill the gap. All the things I wish to discuss are considered by examples from everyday life, almost without any mathematics. I think, the best way to explain a general Law is to recognize a similarity or coincidence in some examples, quite different at first glance.The first example we will use to show the main assumption in the forthcoming discussion, the assumed equilibrium of the state of considered events. The difference between it and non-equilibrium is evident from the Fig.1.

Mountain bike

Great things are done when men and mountains meet.
This is not done by jostling in the street. (Anon.)

You are staying with your bike at the top of a hill. When going down, even without using pedals, you will move with significant velocity. Your mass (you+bike) times half of the square of velocity **nearly** equals your weight times the height difference between the top of the hill and your actual position at the moment. Why we need to underline "nearly equals". It is to be exactly equal **if there is no friction**.
What is friction shows us an everyday experience: there always exists a force directed opposite to velocity. In the case of a bike it is the friction of the wheels and resistive action of air. Due to the mentioned above friction (we call "mechanical") you can never reach the same height on the next hill without using pedals.

We used to say on the matter, that on the top of a hill you have a potential energy. Going downwards you have a kinetic energy, which nearly equals to the change of potential one. We expect the conservation of energy according to the Law of its conservation, stated by Robert Julius Mayer in 1842.The deficiency equals to the friction work, which is friction force times your path downward. The natural question of a curious boy, where is the deficiency of kinetic energy going to. If you rub your palm over a carpet you feel the temperature rise: the friction work produces heat. The heat might be very intensive, it might melt metals in the friction welding devices. On the Fig.2 the friction work is the total work done by a man rotating the pedals. His eager wife is using the friction work to boil some water for cooking.

The first experiments showing the equivalence of friction work and heat were made by James Prescott Joule. In his lecture "On Matter, Living Force and Heat" in St.Anna Church Reading Room, Manchester Apr.28,1847, he stated :" Experiment had shown that wherever living force is apparently destroyed or absorbed, heat is produced. The most frequent way in which living force is thus converted into heat is by means of friction. In these conversions nothing is ever lost. The same quantity of heat will always be converted into the same quantity of living force". Here living force is what we now call kinetic energy.

We wish to add the only one comment to these very important words (found in an excellent book by A. Lightman,Great Ideas in Physics, NY,McGrow-hill,1992) . The last sentence clearly expressed the energy conservation law, but contradicts to the another, not less important Law of Nature, the Law of energy degradation. Actually, all heat can never be converted into kinetic energy of moving bodies, which discussed J.Joule. Only some part of heat can be converted, we will speak about it a little later.
Here we need to accept, that mechanical friction produces some heat at the temperature of sliding surfaces.

Waterfoll

...and again I hear
These waters, rolling from their mountain-springs
With a soft inland murmur. (Wordsworth W. Lines Composed a
Few Miles above Tintern Abbey)

We see more or less the same phenomenon looking at a waterfall. The falling from a dam water, which was at rest before the dam, might flow with a great velocity. Its kinetic energy **nearly** equals to potential one before the dam. The difference is caused by so called "hydraulic friction" the shear of water layers near the channel wall. Behind the dam, at the bottom, where water is at rest again, its temperature should be a little higher, however its rise in practice is very small. The same great man James Joule in his Switzerland vacation tried to measure it by a thermometer with 0.1 C scale and failed to detect any rise.

In order not to lose energy of water, but instead to use it to produce power, a turbine should be installed on the way of falling water. Turbine blades rotate and convert the potential energy of water into shaft work. Then in an electric generator some power is produced. The obtained electrical energy is less, than energy of falling water due to the two kinds of friction : mechanical friction of water over the walls , turbine blades and that of lubricants in journal bearings and a new important kind ,electrical friction in conductors.

Electrical friction

We can transfer electrical charges in solid (metals), liquid (solutions) and gaseous conductors. The flow of electrical charges we call current carries electrical power.In most cases the amount of positive and negative charges is strictly equal, it means the conductor as a whole is electrically neutral. In metals the positive charges are fixed in the crystalline lattice, wherever the negative ones (electrons) form the electron “gas”, which flows in a conductor similar to a neutral gas in a pipe, however with the lattice as obstacle. Electrons collide with fixed particles, which creates a kind of retarding force for electron gas, we call it “electrical friction”. It is actually the same as electrical resistance, which produces Joule’s heating of a conductor. We use this heat in innumerous cases at home when ironing trousers or boiling water. The last is depicted at the Fig.2 (b)when electricity is produced by a man, seeking a physical exercises. This heating might increase the temperature of a refractory metal up to 3000 K, as everybody might see in a filament of a bulb.

Liquid conductors are used much less, than the solid ones, however enough to be mentioned. For instance, the simplest water heater (not for tea !) uses the ability of fresh water to conduct electricity by means of moving ions. This device might convert exactly all power into heat in full accordance with the first sentence of J.Joule .. Here electrical friction is just viscous mechanical friction of liquid around ions as very small spheres. In salty (sea) water ion concentration, hence electrical conductivity, is much higher, than in fresh water. Much less voltage is needed for conductive heating of salty water..

Gaseous conductors are mixtures of neutral particles, ion gas and electron gas. Here the collision of particles not only originates friction, but also splits the neutral particles, producing electrons and ions. Such a mixture is called plasma. 99% of substance in the Universe is in plasma state. Our Sun is entirely plasma, where 4 mln ton of hydrogen per second is converted in helium by thermonuclear reactions. Electrical friction much influences on the Sun’s plasma behaviour. You may see innumerous plasma conductors nightly in the streets of our cities, forming announcements and ads. This plasma is called “cold”, ions and neutrals do have ambient temperature and only electron gas has high temperature. Electrical friction here depends upon electron gas only.

Carnot analogy

> “Daddy, I’ve thinked of a secret surprise... You look just like a carp-fish with its mouth open” (Kipling R. How the Alfabet was made).

It is in the nature of children to find and immediately indicate a similarity of different things. As usual, it does not have any serious consequencies, like in mentioned case with the daddy looking like a carp-fish. In some rare cases the similarity (analogy) found by a clever boy had great consequency in all Physics.

The notorious man in the French history, Lazar Carnot, aside to his duty as a Napoleon’s minister, was an excellent hydraulic engineer. He knew everything on the conversion of water energy into mechanical power by means of turbines : the power is nearly equal to water flowrate times the water height .His genial son Sadi Carnot since his childhood knew the rule :flowrate times height . He understood some similarity between the height and temperature and between the water flow mechanical power and the flow of heat. For the counterpart of the weight flowrate of water he imagined a flow of a special liquid, which he called “caloric”. In his mind the heat flow was the caloric flowrate times temperature. The heights difference of water corresponds to the temperature drop in a heat flow.

Every analogy does not mean identity. Temperature, as we know now is measured from an absolute zero, whereas a height ‘s zero is arbitrary, however it doesn’t matter when we consider differences. Unlike any other liquids, the caloric is weightless, it neither evaporates nor freezes. These minor differences did not prevent the universal acceptance of Sadi Carnot theory. As a military engineer he published his views in a book which has become in 1824 the first textbook on heat engines, when the author was at the age of 28. He formulated the maximal fraction of heat flow, convertible into power. It is the ratio of the temperature difference in and out of heat engine to the absolute temperature at the entrance of heat (Carnot factor).

As the temperature at the exit of heat is not less, than the ambient one, the convertible fraction is significantly less unity. To increase it thousands of engineers after Carnot tried to increase entrance temperature in heat flow conversion. Now the highest temperature in gas turbines is about 1700 K (Degree of Kelvin). If ambient temperature is about 300 K, the maximal fraction equals (1700 - 300)/1700 = 0.82.

Due to all kinds of friction the best attained already in practice efficiency of combined unit with gas and steam turbines is 0.60. This shows the invalidity of the last statement by J.Joule on the total heat convertibility.

Let us focus now on the most unusual property of the liquid “caloric”, assumed by Carnot and his contemporary colleagues : it can be born from nothing, from no substance. To produce caloric only a friction is needed, mechanical, electrical or thermal (see below)one.Important transformation of the concept on caloric had happened in some decades after Carnot, mainly by Rudolf Clausius. He showed, that as a liquid the caloric does not exist. He introduced the word “entropy”, which become the most widely used, popular, difficult and sometimes misleading word in Physics. We do not feel ourselves much comfortable with this word and in present text prefer to keep the old word caloric. We understand, it is a step back. However it is only one step back to make some steps forth.
Hence, as in times of Carnot, speaking on a heat engine or a home battery we count a heat flow as temperature times caloric flowrate.

Thermal friction

I am a doughter of Earth and Water
And the nursling of the sky,
I pass through the pores of the ocean and shores
I change, but I cannot die. (Shelley, The Cloud)

Sadi Carnot stated in his great book that to produce maximum power from a heat flow there should never be a temperature change without a volume change. Volume change means expansion, when temperature declines (if no heating) or compression, when it increases (if no cooling). However, in reality there exists unavoidable heat flow if there is a temperature difference. In real life temperature change and associated flow of heat exist everywhere. Sometimes we try to diminish this heat flow and install a thermal insulation as we do for our home walls. Sometimes we need to transfer thermal energy through a wall of a heat exchanger, trying to make the wall more heat conductive.

According to Carnot, every heat transfer over a significant temperature drop is the loss of our ability to do work. Why is it consistent with his analogy between temperature and height of water ? Imagine, that water is flowing down after a dam through a bundle of very thin pipes with a great internal surface, hence large friction. Water velocity would be low and its kinetic energy negligible, even though the total flowrate is large. Instead of pipes here might be a sponge or another porous body, like a thick layer of sand. Here the product of water flowrate and height equals friction work, heating the bottoming water. Potential energy of water is converted into heat. Amount of born caloric here equals to the friction work, divided by water temperature.

Very similar process takes place in a heat transfer through a wall, having a hot and a cold side. The heat flow entering the wall exactly equals to leaving one, however the caloric flow should increase because the temperature of leaving heat is less. Here we see unavoidable caloric gain in a heat transfer through a wall. The more is the temperature difference, the more is the caloric gain. We call the phenomenon “thermal friction”. We can never distinguish the caloric born in mechanical friction from that born in the thermal one. That’s why we call the mechanical, electrical and thermal as **generalized** friction. In modern Energy Engineering exists very well developed method of thermal devices design, using minimization of the sum of mechanical and thermal friction which corresponds to minimum of caloric gain.

Strictly speaking we are obliged to indicate the fourth kind, the “chemical friction”. Every chemical reaction gives birth to some quantity of caloric. It is a more difficult part of the science on exergy and we prefer not to overburden our readers. If they would be interested in, they might find an extensive discussion elsewhere.

At first glance one may eliminate thermal friction by nearly zero temperature drop in a wall. As usual it is misleading, because the less temperature drop is the more the wall surface should be and for a large wall production we are forced to produce much more caloric, than we saved in temperature drop decline. When we deal with time specific processes with periodical heating and cooling the small temperature drop leads to very large time span due to very slow heat transfer. Always there exists an optimal temperature drop.

In every case of generalized friction the amount of born caloric is friction work, divided by temperature at the point. The mechanical friction work is friction force times the path, the electrical one is current times voltage drop in a conductor, the thermal friction work in a heat transfer through a wall is proportional to the heat flowrate times the temperature difference. If the lower temperature coincides with the ambient one, thermal friction is maximal.

Otherwise, if not in heat transfer, this fraction of heat flow according to Carnot analogy, might be totally converted into power. But in heat transfer it is completely lost for power production.

A warning

Now I wish to define more clearly, what we are speaking about.
The Matter of the Nature consists of the substance and the field. The latter occupies all the empty space. Energy currents exist either in a substance or in a field. Energy currents in substance discovered Russian physicist Nicolay Oumov in 1874. Energy currents in the field carried by electromagnetic waves discovered by J. Pointing in 1884. These currents might be either very weak, for instance about 10^{-15}W/sq.m from a handy phone in your pocket to about 10^{+15}W/sq.m in a powerful laser beam. The difference is in 30 orders of magnitude. The process which might be considered as a friction in the field energy currents has a special nature, it is not discussed in the present paper. We restrict ourselves within the limits of energy flows in substance only. Every substance consists of particles, bounded (solids, liquids) or unbounded (gas, plasma). The interaction of particles transfers energy and creates friction.

Rubber balloon

In Siberia's wastes
The ice-wind breath
Woundeth like the toothed steel...
(J.C.Mangan, 1803-1849, Siberia).

In a winter day you carry a rubber balloon from a cold street to a warm room. Look at the balloon (Fig.3) It will expand, the radius of the sphere is increased till the temperatures of air inside and outside are equal. The expansion produces the mechanical work of two kinds: 1) against the rubber tension, 2) to shift a part of air out of the room. We suppose, the reader is familiar to the arithmetic of quantities, denoted by characters. The mentioned expansion process is described according to energy conservation law: the change of internal energy of the air inside balloon (the sum of kinetic energies of air particles in their chaotic movement) is increased due to heating from room air through a rubber wall and decreased due to expansion work production. The same process we may observe when transfer from a cold street into a warm room a vertical cylinder with air, compressed by a heavy piston able to move in the cylinder without friction . When heating in the room the pressure inside cylinder remains constant, it is the piston weight divided by its surface. But the air expands due to temperature increase and occupies more volume, producing some work for the piston elevation. It is the same work ,which in the rubber balloon is produced against rubber tension.
In both cases, according to energy conservation law, the change of internal energy of the heated portion of air ΔU equals the external heat obtained from the room with temperature T_o : $\Delta Q = T_o\Delta S$, less produced work $P\Delta V$. The last consists of the two parts, the work against rubber tension or piston elevation and the work, needed to shift some air from the room to outside by the room pressure P_o, so

$$\Delta U = T_o\Delta S - (P - P_o)\Delta V - P_o\Delta V \quad (1)$$

Here U= internal energy, T= temperature, P= pressure inside balloon or cylinder, V= volume. T and P in the room are indicated by subscript zero. The caloric amount is denoted by S. The reader should remember this letter for the future, when he will be forced to change the title of the symbol. The increase of caloric ΔS inside the heated balloon is caused by the heat flow from the room **and the thermal friction in the heat transfer through the rubber wall of the balloon or the wall of cylinder.The understanding of the last part of caloric flow is of primary importance for the following definitions**. It might be almost zero if the heating process is very long due to very small difference of temperatures inside balloon and in the room. In other words, if here the thermal friction is absent. Actual temperature difference is as it is, but as an important assumption we may neglect here the thermal friction and in the next formula evaluate the maximal work done for rubber expansion or the piston elevation, the work without friction.

This work is the second term on the right hand side, let us denote it by A.

$$A = \Delta U - T_o\Delta S + P_o\Delta V = \Delta(U - T_oS + P_oV) \quad (2)$$

Our room is very large with respect to the balloon or cylinder. W hen they enter the room the numbers Po and To do not change, we may assume these as constants. That is why we transfer the difference symbol Δ outside brackets. The temperature difference in the example is rather small, about 20 C, even in the heart of Siberia it does not exceed 80 C. In Siberia outdoors it might be very cold indeed (-60 C).

What is exergy ?

Man raises but time weighs. (Library of US Congress ceiling sentences)

Equation (2) for the obtained work was first formulated by the American physicist Josiah Willard Gibbs in 1873. It is valid not only for a balloon, but for all cases of thermal engines. If kinetic energy or a potential one plays a role, it might be simply added to internal one. The most important term here is the last one, reflecting caloric gain. The term A was first called "availability" or "available energy". Following the proposal of Z.Rant since 1956 it is referred to as "exergy".

Exergy indeed, unlike energy measures the ability to do work. This ability much depends upon the reference state. As we have seen, energy flows always are accompanied by a friction of some kind causing energy degradation. This law of Nature is not less universal and important, than energy conservation Law. The general definition:

Exergy is the maximal work, attainable in given reference state without generalized friction.

In the closed system energy is conserved but exergy is destroyed due to generalized friction.

Exergy value might be attributed to a substance, like a fuel or metal or chemical compound. There are good tables for it, made mainly by professor J.Szargut in Poland. Exergy flow might be described by a vector, similar to energy vector. For a given heat flow Q* the exergy flow is Q*multiplied by Carnot factor (T - To)/T. When the temperature is approaching the ambient one (reference), the exergy vanishes even though the heat flow is still large.

Have a look now at the Fig.4. It vizualizes the process in a heat engine. From the left to the heat engine are going energy units (heat). They are equal, but only a fraction of it might be elewated to the work level, a large fraction should fall to the ambient level. But without the fall the elevation is impossible. The higher is the level of coming units (temperature) the more is fraction of the work obtained. Exergy is the measure of this fraction if the heat engine is ideal (Carnot's one).

If the process temperature T is less, than the ambient one To, the direction of exergy flow is reversed. It takes place in the heat transfer through a wall of the freezing chamber of a home refrigerator. The cooling process by the use of work is presented in Fig.5. Work consumption let us extract thermal energy units from the cold freezing chamber and elevate them up to ambient, thus compensating the energy units, which penetrate the thermal insulation of the chamber. Exergy of the cooled substance is the measure of needed work.

In general, in the refrigerating problems exergy is greater, than energy. It is wrong to consider exergy as a fraction of energy. Energy in a vessel with liquid helium is very small, whereas its exergy is quite large, it let us even power production by a turbine, unless the temperature inside is low enough.

Gibb`s finding of a proper function, now called Exergy, conquerred all the branches of Thermodynamics, Energy Engineering and Chemical Engineering. The amount of published papers reached many thousands. Exergy now is an unavoidable term of engineering language. The time really weighs. That is why we think, it is worth of your attention.

Reference state

A sea of stagnant idleness,
Blind, boundless, mute and motionless
(Byron. The Prisoner of Chillon).
We are such stuff. As dreams made of, and our little life is rounded with a sleep.
(Shakespeare, The Tempest)

For the mentioned balloon the reference state (surrounding) was the air in the warm room. Its temperature and pressure doesn't depend upon the balloon properties anyway. In other cases when we use the word „exergy" we should immediately think, what reference state is here. For many tasks the role of the room might be played by the atmospheric air or, as in the case of a power plant, a water basin or a nearby river. In any case the "surrounding" should be something big enough to be independent from the body we are dealing with. If it is atmospheric air we should bear in mind the seasonal and diurnal change of temperature. Exergy of ice is about zero in winter (by To less 0 C), but it is quite significant in hot summer day by To about 30 C, look at Fig.5.

When we look at the aquarium with coloured fishes in the cockpit of a submarine, the air in cabin is its surrounding and the reference state, however when considering the heating or cooling of this air for the comfort of the crew the reference state is the sea water outside by pressure of many tens of bars.

In a space ship case there is no surrounding substance, but a relict radiation of about 3 K temperature exists in the Universe. Perhaps, it might be the reference one.For the fleet of space ship the exergy concept has not been yet developed, no papers have been published. It is a job of future generations of researchers.
To those of the readers, who like difficult and rather philosophical questions we leave one: is it possible to define the exergy of the Universe itself as it has no surrounding ?

Exergy unit

Everybody knows, a mass is measured in kg, length in m, energy in J e t.c. What are the exergy units ?
As exergy is not energy it is unwise to measure it in energy units J. The offered but still not widely accepted is the unit of exergy **gibbs (Gi).** In case of mechanical and electrical energy 1 Gi = 1 J, but in case of thermal or chemical processes 1 Gi not equals 1 J. 1000 Gi = 1 kGi, 1 mln Gi = 1 Mgi and so on.
Look at Fig.6. If to assume, that exergy inflow from coal is 100Gi, we may replace % by Gi on arrows. The arrow 4 which reflects the exergy losses in power plant boiler should be 5 times less if we measure these losses in Joules because energy losses in boiler are about 9 %.
Let us consider the table with figures for the comparison of steam properties before and after the steam turbine at a big bower plant. The reference temperature for exergy calculations 300 K or 27 C was taken.

Temperature, K	Enthalpy, kJ/kg	Carnot factor	Exergy kGi/kg
900	3600	0.67	2400
315	2500	0.05	125
	(69%)		(5%)

From the table is seen, that completely used steam after expansion in turbines still has about 69% of its initial energy (enthalpy) before expansion, whereas its usefulness (ability to do work) is almost nil. In real economics the price of steam needs cumbersome tables with different prices for different steam temperatures regardless of its energy content.
If the steam price is proportional to the exergy content, expressed in kGi/kg it would need only one figure X $/kGi.

Exergy efficiency

Better than all measures
Of delightful sounds
Better than all treasures
That in books are found
(Shelley, To a Skylark).

For energy management the most important figure is efficiency: how much useful energy we have from a given energy source. If to ignore exergy and compare different units by energy efficiency only (ratio of energy output by energy input), it is often misleading and shows the efficient use, when actually it is not so. Let us compare the energy and exergy efficiencies.

	Energy	Exergy
District heating boiler	0.85 - 1.05	0.15 - 0.18
Power plant boiler	0.90	0.50
Power plant	0.40	0.39
Cogeneration of power and heat	0.85	0.40
Electrical water heater	0.33	0.06
Heat pump	1.20	0.20

In all cases the numerator is the delivered energy or exergy flow and the denominator is equal to fuel flow energy or exergy. It means that the electrical heater and electrical heat pump are considered together with a fuel-fired power plant. The numbers of energy efficiency exceeding unity are due to neglecting of vapor condensing in the boiler heating value of fuel or neglecting of low temperature heat for a heat pump case.

Some very different numbers of the both efficiencies are spectacular. Both boiler cases do have very high energy efficiency. An only energy-minded engineer will never try to improve anything there. However for an exergy-minded manager or engineer the big thermal friction work over the temperature drop about 1000 C is evident and he really has an opportunity for improvement. When a user needs the heat of different temperatures the best remedy against exergy destruction is cascading, heating in series one boiler by the flue gases of another one with higher temperature.The exergy efficiency is the best measure indeed, it shows clearly how wise we operate.The difference between efficiency and unity shows the exergy destruction rate.

Almost equal figures for power plant efficiencies are caused by equal numerators (electrical power is pure exergy) and nearly equal heating value of fuel and its exergy. But nearly equal results contain the biggest difference inside. Energy efficiency shows erroneously the steam condenser as the culprit of losses, whereas the exergy one correctly shows the thermal friction in the boiler. Let us try to visualize this.

Where exergy is lost ?

And many more Destructions played
In this ghastly masquerade,
All disguised even to the eyes...
(Shelley. The Mask of Anarchy).

The answer is to be seen in the picture with a diagram Fig. 6 . This visualization originated from the Irish engineer Sankey more than a century ago. He offered a graph of energy flow, with the width of a strip, proportional to the flowrate of energy in a series of energy conversion processes, following one after the other. Then P.Grassman expanded the diagram on exergy case to show, where exergy is lost.

Have a look at the Sankey-Grassman diagram for exergy flow in the conversion of coal into electricity at an ordinary coal-fired power plant.The exergy of coal in the depth is assumed as 100%. It is a national reserve, which should be consumed most efficiently.

In a coal mine with the work expenditure to crash and elevate coal, first 6% of exergy are lost, see arrow 1. Then the coal should be enriched, i.e.the rest of the rocks should be separated. Here some work is needed and some coal is lost, which forms the exergy losses of 4%, arrow 2. Enriched coal is delivered to the power plant, next 3% of exergy are lost due to mechanical friction in transport, arrow 3. When the coal is burnt at the power plant we see the greatest exergy losses: 43% is lost in combustion and thermal friction, when heat is transferred from combustion gases by 1600 C to steam at 600 C (temperature drop of 1000 C), arrow 4.

Expanding steam drives the turbine coupled with the electrical generator, which produces electrical power. Here 10% of exergy are lost due to mechanical friction in turbine (steam over a wall, journal bearings) and electrical friction in the generator. Exergy losses in the steam condenser are also present, they are small because the temperature of condensed steam is very close to ambient (reference point). In an electric line then about 3% of initial exergy are lost entirely due to electrical friction.

In total, only 31% of coal exergy are delivered to a consumer of electricity. Here the power plant efficiency (34%) refers to the coal in depth. If relate it to the amount of coal, delivered to the site of power plant, it is 0.34/0.87 = 0.39. Exergy losses are disgguised indeed, especially its destruction due to thermal friction.The diagram shows, that the culprit of exergy destruction is the boiler of power plants, here the losses exceed all the others, even taken together.

Exergy flow direction

As we see, exergy is relating to energy, but a quite another function. It coincides numerically with energy when we deal with mechanical or electrical energy, but strongly differs for thermal and chemical energy. If anywhere exists an energy flow it always is accompanied by associated exergy one. They might differ not only by greatness but also by direction (sign). Thermal exergy flow is directed always to a body with ambient temperature, whereas thermal energy flows toward lower temperature. If the process temperature is higher, than ambient (reference) one, the direction of energy and exergy flow is the same. If we deal with a home refrigerator, cryogenics or other cooling machine, the temperature of a flow is less, than ambient and exergy flow is opposite to energy one.

. At the end of 19 century there were two neighbours, a brewer and a butcher. The butcher's schop was inbetween the two brewer's rooms. In the left room brewer installed a cooling machine, which produced rather cold salt solution to cool a vessel with the beer preparation, located in the right room.The butcher admitted to conduct the pipes with cold fluid from the left to the right room through his shop. When he recognized, that pipes are under thick layer of ice he began to store his meat around the pipes, using it as a free refrigerator. However this immediately spoiled the beer technology and brewer put the accident on trial of municipal authorities as for a theft. What has been stolen? -asked the judge. My energy, answered the brewer. But butcher easily derived, that he is not a thief of energy, but rather a sponsor of it due to fact, that energy flows from warm meat to cold pipe and he won the process. Had the brewer were so clever as to answer : my exergy, he would have been the winner.

Exergy from ocean

The sun is warm, the sky is clear
The waves are dancing fast and bright...
The lightning of the noontide ocean
Is flashing round me...
(Shelley. Stanzas)

In 1881 the French physicist D`Arsonval attracted attention to a natural phenomenon, the difference of temperature of the upper and the lower layers of tropical ocean's water: about 30 C above and 5 C below (deeper 600 m). He offered to use this difference to produce power.

As we have learned already from Sadi Carnot , to produce work from heat we need the temperature difference. In the air the difference of 20 C is rather small, it is enough to transfer heat through a wall and nothing more. But in water with high density and heat conductivity it might be enough to produce power.

The only source of heat of upper water layers is evidently the Sun. The source is abundant and clean. If we conduct a flow of upper water downward through a pipe of 1 sq.m cross-section at a velocity of 1 m/s, the flow of exergy is this: density times velocity times heat capacity times temperature difference (still it is the thermal energy flow) times the ratio of temperature difference to absolute temperature of upper water (about 300 K). The last ratio is Carnot factor, it converts the thermal energy flow into exergy flow.
Having made the calculations we get:

1000 kg/ cub.m . 1 m/s . 4200 J/kg.grad . 20 grad. 20grad/300 grad = 5600 kW/sq.m = 5600 kGi/s.sq.m

Here 4200 J/kg.grad is heat capacity of water and kW of exergy = kGi/s

We have to compare the exergy flow in the pipe with the solar energy flow density in space near to the Earth : 1.3 kW/sq.m. It is called "solar constant", the falling energy from the Sun on 1 sq.m plate. perpendicular to the light path. Falling on ocean even in tropical regions averaged incident radiation is much less due to clouds and diurnal variations, it is at most 0.3 kW/sq.m. We see that exergy flow of the ocean water is fifteen thousand times more dense, than averaged radiation. It means, ocean is not only absorber of exergy in solar light, but also the concentrator of exergy.

High exergy flow density of ocean water stimulated a great activity to find a practical solution of old D'Arsonval idea and to build a power plant, using upper ocean waters like a "fuel"to a boiler. The scheme of such floating power plant entitled OTEC (Ocean Thermal Energy Conversion) is depicted on Fig. 7 . It is a hermetically closed loop, filled with easy boiling substance (freon) . Unlike water this substance might evaporate and condense just at the mentioned ocean water temperature: upper water is heating the evaporator and cold water from below cools the condenser. The liquid freon is pumped to evaporator by elevated pressure. Inside a loop a turbine and generator are installed.

There are many such experimental plants in the world, where difficult engineering work is underway to create a real engine working on the heat from the ocean. Especially active and successful are japanese engineers.

Now we are ready for an important "gedankenexperiment" as A.Einstein referred to such practice.(The example taken from the book by W.Haefele et al. Energy in a finite world, Ballinger,1980). Look,please, at the Fig.8.

Let us imagine, that we have such ocean engine, in which a small part of thermal energy of the upper water is converted into power and the rest part of energy in condenser is given to the cold water below. Imagine also, that near to floating power plant is floating a cylinder with air and piston and we consumed all the generated power to shift the piston and compress the air inside. During compression the temperature inside floating cylinder not increased due to heat transfer to the upper water. Exactly the same energy, which was taken in the engine as mechanical power, is returned to ocean water, there is essentially no energy change. In the compressed air occurs no change either, because thermal energy of air (kinetic energy of air particles in chaotic movement) remained the same, as before compression. What really changed ? The temperature profile in the ocean due to heat transfer, it means due to thermal friction. Exergy of ocean has become a little less. This decline is very difficult to calculate. But gained exergy inside the cylinder is calculated very easy. It might produce work. We may take the cylinder and carry it far away from ocean to a city .

In the city we may imagine a car with pneumatic engine, working on compressed air. We may install there our cylinder and to move on a significant distance. Produced work against mechanical friction in the movement is converted into heat by ambient temperature, which exactly covers the cooling of air due to its expansion in the pneumatic engine. There are no changes in energy, but exergy of the air in the cylinder is completely lost for the wheels driving.Here we see the production of exergy, its transportation and use: a car movement. It is very difficult, if not impossible, to explain what really happened in the ocean and the city using only energy terms. Energy did not changed either in the ocean or in the city.

Heating of dwellings

She picked out a nice dry Cave... and she lit a nice fire of wood at the back of the Cave, and she hung a dried wild horse skin, tail-down, across the opening of the Cave. (Kipling R. The Cat that Walked by Himself)

In the Stoneage, when people used to make their dwellings (cave) warm by a fire inside, almost all the heat produced remained in the dwelling. However, aside to heat, there remained unpleasant combustion products. This was changed thousand years after by decoupling fire gases flow and dwelling space, thus eliminating unpleasant breathing of combustion products. But this drastically declined the heating system efficiency. Stack gases took away a lion share of produced heat. Since the old ancient times the amount of fuel, spent to heat dwellings has greatly increased.

In such northern countries as Canada, Russia, Scandinavia and in cold years Britain, the fuel consumption for heating dwellings is the major part of national energy balance. It is important to understand, that almost all the dwelling heating is the thermal friction and exergy destruction.

We wish to avoid any cumbersome calculations. Imagine, that thermal insulation of boiler houses and water pipes is perfect and heat flow Q* is constant from a boiler to home battery.
The flue gases averaged temperature is about 1100 K and the reference temperature (air outside) is 270 K. The fraction of Q*, the exergy flow equals (1100 - 270)1100 = 0.75 Q*. In a home battery the temperature is admitted at most 90 C or 363 K. Here the exergy flow is (363 - 270)/363 = 0.25 Q*. If to remember the exergy destruction in combustion and some hydraulic friction the mentioned figures of exergy efficiency 0.15 - 0.18 are evident, it means the **one sixth of fuel exergy only** can reach the consumer. Much less fraction of the fuel exergy can reach the home room when we use the electrical heater, it is about 6% only (see Fig.9 and efficiencies table).

The first man, who understood the great possibility of fuel saving in heating was William Thomson (much later lord Kelvin). In 1852 he published the paper “On the economy of heating or cooling of buildings by means of currents of air “. There the idea of “heat multiplier” was described. It comprises an air expander, a heat exchanger, a compressor and a heat engine. When ambient air expands to a pressure about 70% of ambient, it cools down, then in the heat exchanger it is heated by ambien air and then compressed to an ambient pressure. Its temperature is increased over ambient one , it is enough to be comfortable in a dwelling even when it is very cold outside. Note, that the fuel is used not to heat air directly, but to feed the engine, driving compressor. Instead of great thermal friction the temperature increase is created by an expansion-compression process in accordance with Carnot advise to avoid heat transfer.

W.Thomson optimistically promised to heat houses with 3% of the fuel, used in contemporary stoves. We may wonder, how near is this figure to exergy efficiency of the former inefficient heating systems.This idea gave birth to a big business in the world, where some tens of millions of such machines, referred to as “heat pumps”exist already. They differ from W.Thomson scheme by using many other substances instead of air and being driven mostly by an electric motor. In many cases of big units the drive by heat engines, either piston or turbine, is used also. No one heat pump can create a big temperature difference. The more it is, the less is fuel economy.
The principle of heat pump is presented in Fig.10. The still useless energy units from ambient water (low-grade heat) are elevated to higher temperature by means of much less amount of noble work units, coming from the left. The

useful energy, going to the right is the sum of low-grade heat and consumed work. We have seen already in the table of efficiencies comparison that exergy efficiency of heat pump exceeds district heating one and is three times more than that of electrical water heater.

The challenge to future heat supply engineers is the figure of attainable exergy efficiency of about that of power plant, it means 40% instead of today's figure of not more than 20%. It will give tremendous fuel saving and seems to be economically justified.

Concluding remarks

The history of the World is the biography of great men.(Library of US Congress)

First we wish to show our observations, when looking at the greatest achievements of classical Thermodynamics as the basis of its exergy branch. We had found the years of publishing of the most eminent contributions and the year the author's births. Having distracted the latter from the former, we got the following:

	S. Carnot	R.Mayer	R.Clausius	W. Thomson	N.Oumov
Contribution published	1824	1842	1850	1852	1874
Authors born	1796	1814	1822	1824	1846
	------	------	-----	-------	-------
	28	28	28	28	28

Looking at this magic number 28 we used to repeat to our readers: hurry up. You don't have so much time. For the contemporary matriculants it is less, than a decade.

Now we try to answer the questions of the curious boy.

Energy is conserved. The flow of energy in an insulated channel is constant. Disappears exergy due to generalized , mostly thermal, friction. That is just exergy we need to produce and save. The rate of its destruction depends on us, on our skill to manage it. Exergy drives all the wheels on Earth. Just Exergy supports life.

The exergy century has come. Fight thermal friction.

Acknowledgement

I wish to express my gratitude to Professor J.Szargut for his critical comments and to Professor M.von Spakovsky for critical comments and recommendation of the lecture by Professor L.Borel in Ecole Polytechnique de Lausanne 28.04.1988 from where the pictures of Fig. 1,2,3,4,5,9,10 made A. Bölcs have been taken.

If anybody of readers is willing to learn more on the subject, have a look on the books and papers where many other books and papers are cited:

Bejan A**. Advanced Engineering Thermodynamics**, J.Wiley, 1988,1997.
Feidt M. **Thermodynamique et optimization energetique**, 2e ed. Tec et Doc-Lavoisier, Paris, 1996.
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Szargut J., Morris D., Steward F. **Exergy Analysis of Thermal, Chemical and Metallurgical Processes**. Hemisphere, NY, 1988.
Yantovski E. **Energy and Exergy Currents**. NOVA Sci.Publ. New York, 1994, 1995.
Yantovski E. **Exergonomics in Education**. Energy-the Int.Journ. No10, 2000. 1021-1031.

There exists a professional journal EXERGY, published by Elsevier.

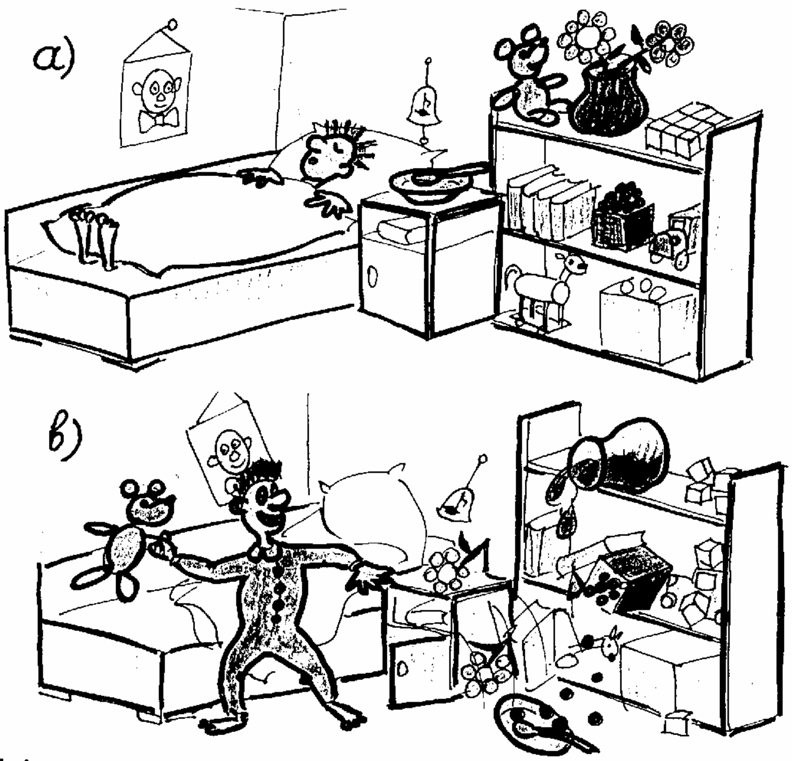

Fig.1. Equilibrium (a) and non-equilibrium (b) state in a very familiar thermodynamic system.

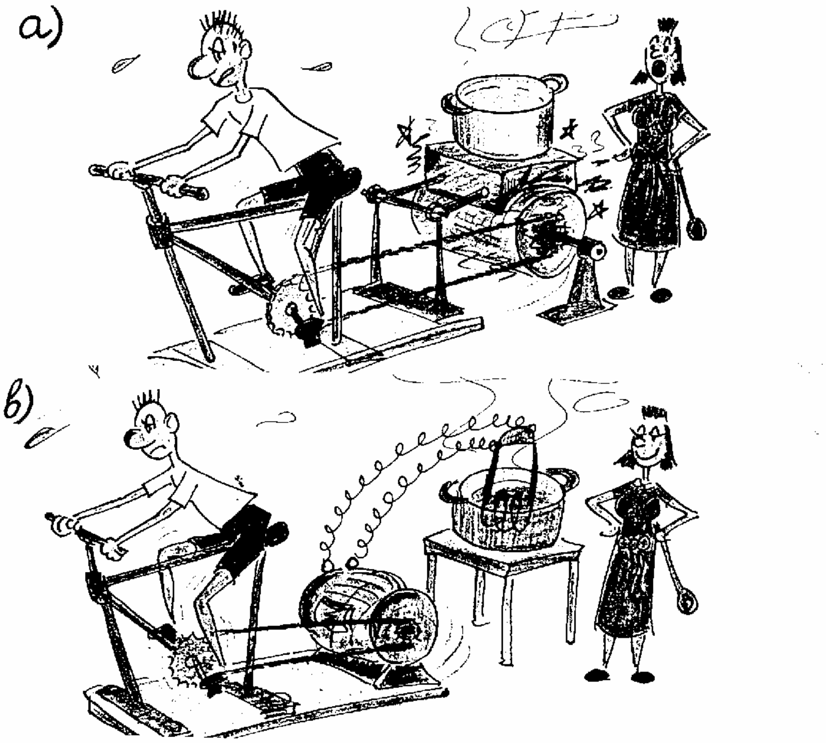

Fig.2. The work conversion

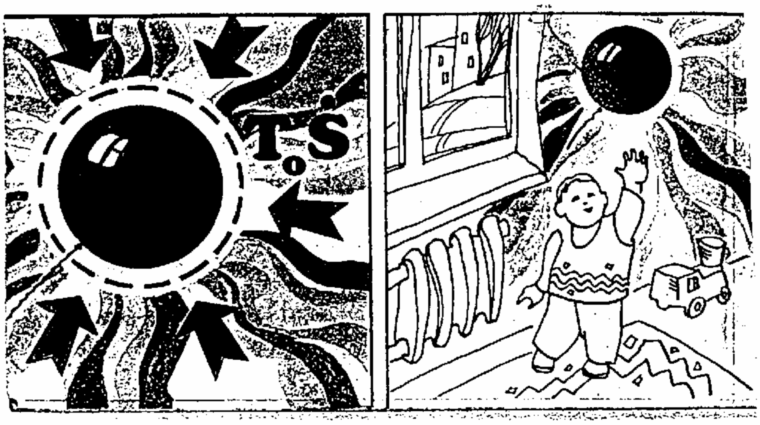

Fig.3. Expansion work of a rubber balloon in a warm room measures the exergy of air in it.

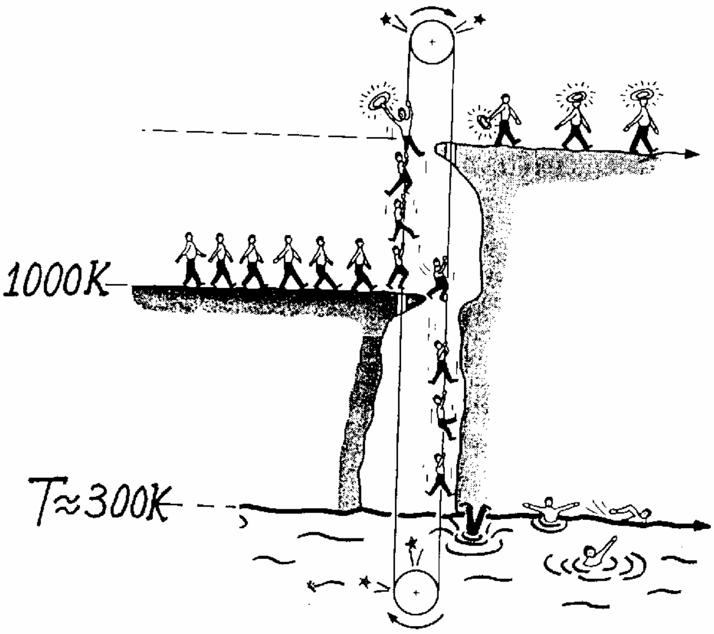

Fig.4. Conversion of heat into work in a heat engine. Maximal work is the heat exergy.

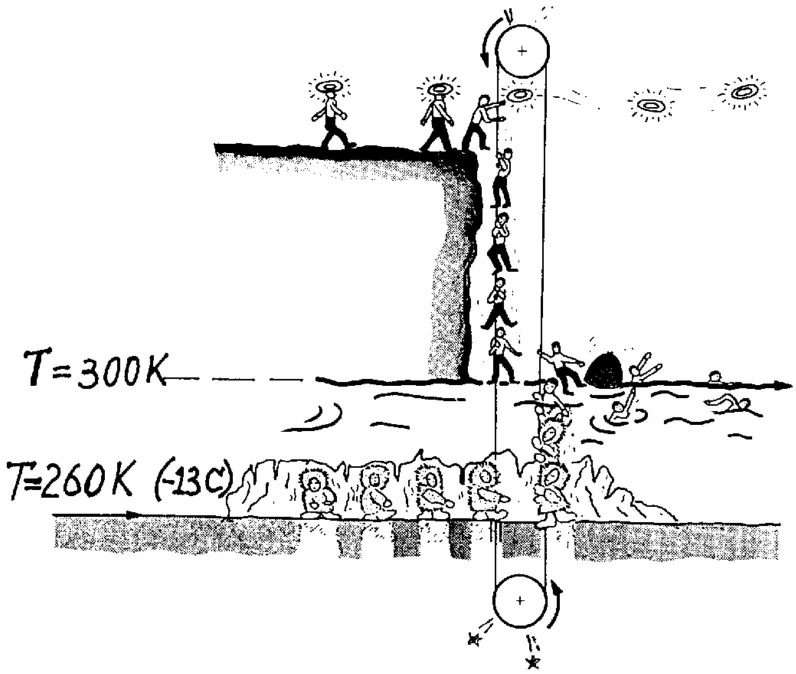

Fig.5. The work consumption for the thermal energy extraction from a freezing chamber of a refrigerator. The least work measures the exergy of coldness.

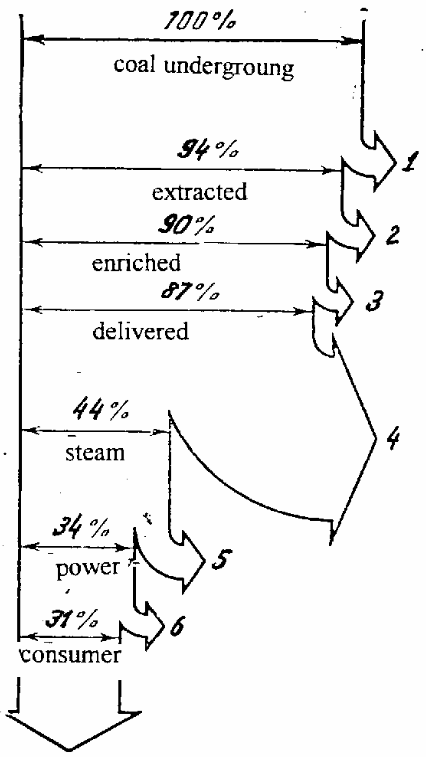

Fig.6. Exergy flow from a coal mine via power plant to an electricity consumer. Arrows

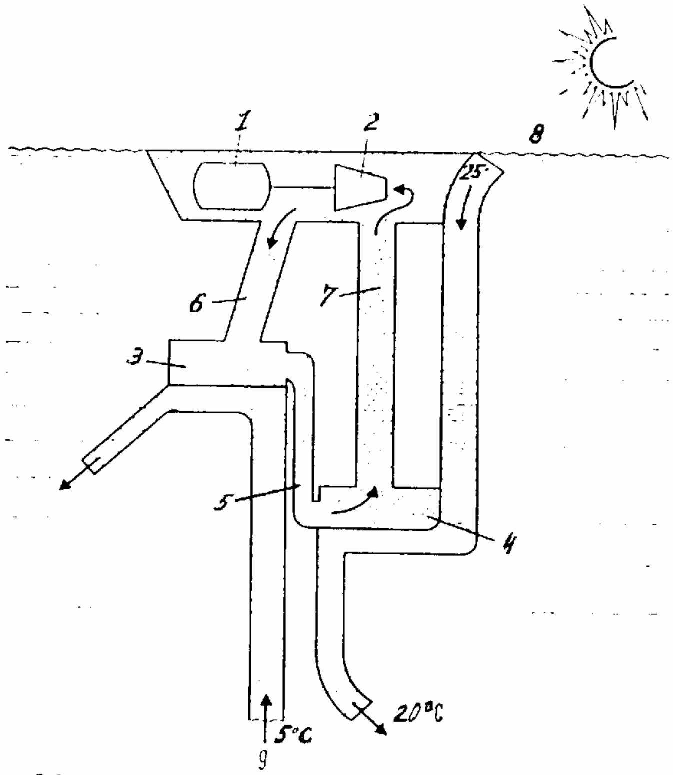

Fig.7. Scheme of the Ocean Thermal Energy Conversion (OTEC) aimed at consuming the highly concentrated exergy of warm ocean water for electricity generation. 1-generator, 2-turbine, 3-condenser, 4-evaporator (boiler), 5-liquid, 6-low pressure vapor, 7-high pressure vapor, 8-warm ocean water, 9-cold water from the depth.

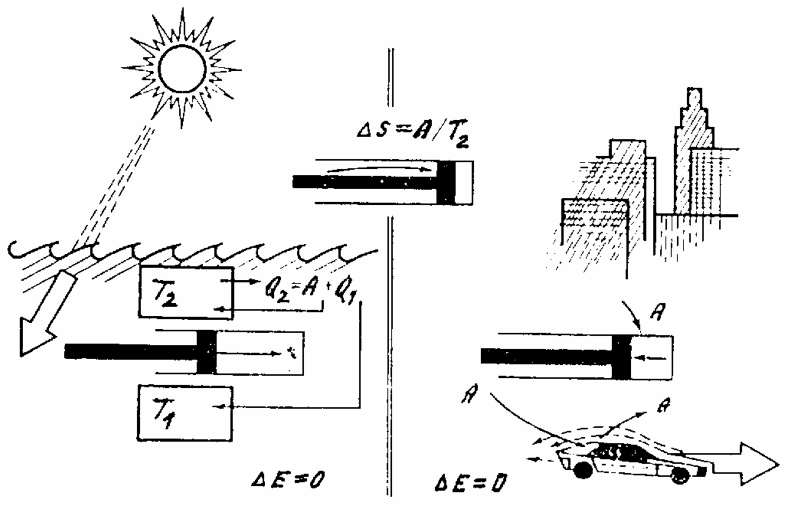

Fig.8. Exergy transfer from ocean to a city by compressed air.

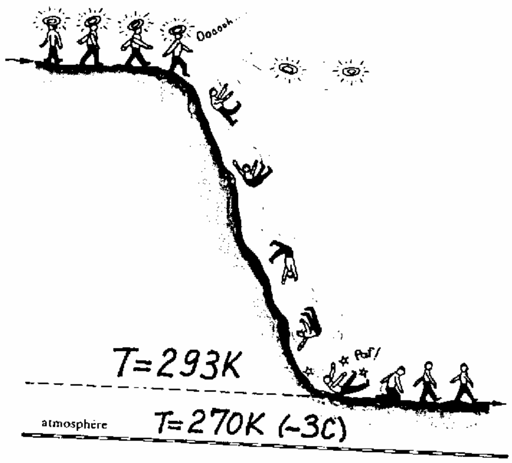

Fig.9. Exergy destruction in the use of electrical energy for the home heating. All the losses are due to thermal friction (not electrical one !).

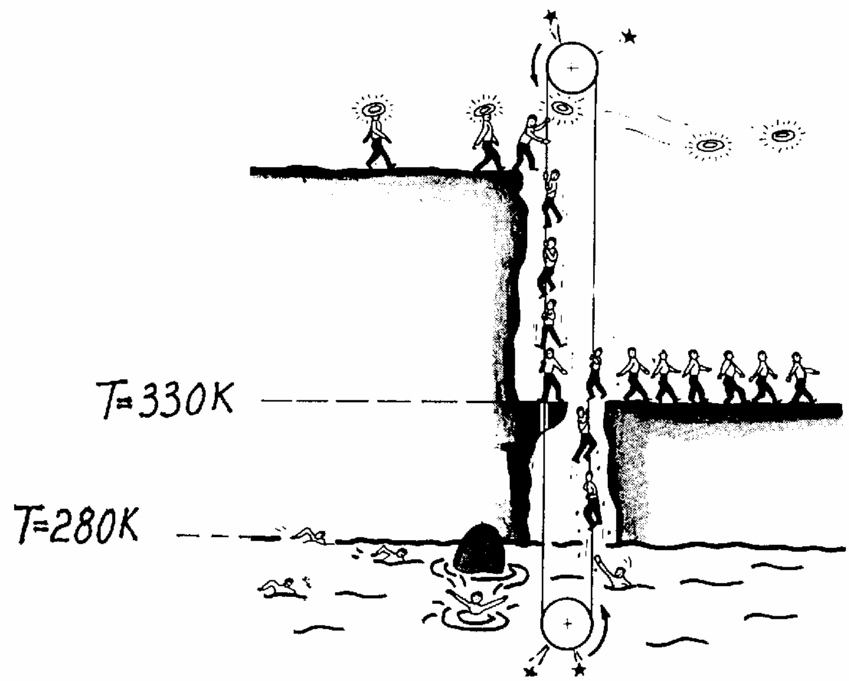

Fig.10. In a heat pump process the useful thermal energy consists of the sum of energy, extracted from the ambient, and the used work. It is many times more, than in Fig.9.

Pictures (made by A.Bölcs) at Fig. 1,2,3,4,5,9,10 have been found (and slightly simplified by us) in the booklet by Professor L.Borel „Thermodynamique, energetique et mutation dans