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Waste energy utilisation — An appeal for an entropy based strategy ☆

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Abstract — The paper gives a review of a project initiated by the Berlin-Brandenburg Academy of Sciences (formerly the Prussian Academy of Sciences) entitled "Waste energy utilisation — A contribution to an entropy economy". It covered not only the technical aspects of a better waste energy utilisation but studied also the social, economical, political and legal implications, as well as existing impediments. As the term entropy economy indicates a purely quantitative assessment of energy and its losses on the basis of energy balances is not very helpful. Instead, entropy balances permit a qualification of energy and the development of strategies for better waste energy utilisation. The paper is meant as a general introduction into the following papers, where technical aspects of a better waste energy utilisation are discussed. © 2001 Éditions scientifiques et médicales Elsevier SAS

waste energy / energy utilisation / entropy economics / low temperature energy / entropy strategy / second law of thermodynamics

1. INTRODUCTION

Energy as well as mass transfer processes obey the laws of conservation after which all of the energy or mass transferred into a system and not stored there is again emitted into the environment of the system. A reduction or use of waste energy, therefore, does not only reduce the ecological damage but also reduces the energy consumption and, thus, the primary energy needed. Waste energy, different from primary energy, is of low quality. In the same state as the environment it is even useless for processes on the Earth.

Energy processes follow, aside from the concept of conservation, also the second law of thermodynamics, which makes statements about the direction of processes and, therefore, about the quality and forms of energy. For processes in stationary systems the entropy emitted is higher than the entropy input, because of the entropy production due to natural processes. They reduce the quality of energy. The entropy law, therefore, is a useful tool to evaluate waste energy and to develop strategies for its use. It is true that the total energy input to technological systems either as primary energy or as solar energy is removed as energy or with the energy stored in the waste products, the energy of which, again, is of lower quality. The reduction of quality can be characterised with the aid of the entropy, because the natural steady-state processes within the system cause an entropy production. They add to the entropy of the energy input, so that the entropy removed from the system is, because of the entropy production and because of additional external irreversibilities, greater than the entropy input.

Furthermore, we can state that the environment with its properties, characterised by their thermodynamic potentials, is a natural reference state for all energetic processes. Energy in the same state as the environment is useless. In order to realise an energy emission through natural processes, we need a potential difference between the emitting system and its environment. The transfer of energy or substances into the environment causes an in-

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crease of entropy, the so-called external irreversibilities which add to the internal irreversibilities due to the entropy production within the system.

2. THE ROLE OF WASTE ENERGY

Nutrition and energy supply of an increasing population are of central importance in the human society. Many needs of our societies can only be solved in a satisfying way if sufficient and cheap energy is available. As a matter of fact, the products and raw products with by far the largest quantities all over the world are primary energy carriers as *table I* shows.

Almost 1/2 of the raw products are primary energy carriers, as this table shows, and if we consider cereals in a wider sense also an energy carrier even 2/3 of the raw production contribute to energy consumption. The mass of other products except cement and water, the latter was not considered here, is at least one order of magnitude, or even more, smaller. Of course, we must find the raw products again as waste. It is not surprising, therefore, that CO_2 mass emissions surpass by far all other waste products as *table II* shows.

Different from the world society around 10 000 years ago, where we had a world population of 5 million persons, mainly living from hunting and picking fruits, and thus disturbing their environment only infinitesimally slow and negligibly, we have now a population of around 6 thousand million persons, and the energy and mass transfer with the environment has reached dimensions that have a strong impact on the Earth as a reservoir. This makes evident that even a long-term strategy cannot maintain our environment in the present state; instead, a responsible treatment of the environment is required in the sense of a sustainable development. As a consequence, in many countries refuse is recycled as far as possible in order to save raw material. In a similar way also waste energy should be minimised, for instance, by "recycling" in order to save primary energy.

TABLE I
World-wide consumption of the most important raw products.

Substance	Annual consumption in 10^9 kg
Hard and brown coal (in hard coal equivalent)	3 500
Crude oil	3 475
Natural gas (in hard coal equivalent)	2 900
Wood (around 45 % for industry)	2 750
Cereal (29 % wheat, 28 % rice, 7 % barley, 5 % millet)	2 075
Cement	1 400
Iron and steel (42 % iron, because of recycling only 45 % of this from iron ore)	1 300
Root vegetables (46 % potatoes)	645
Vegetables and melons	590
Milk	540
Fruits	420
Meat (41 % pork, 27 % poultry, 27 % beef)	215
Fish (19 % from inland water)	110

TABLE II
World-wide anthropogenic gaseous emissions.

Substance	Annual consumption in 10^9 kg
CO_2 (23 % from USA, 13 % from P.R. China, 7 % from Japan, 4 % from Germany)	23 900
Methane (30 % from live-stock, 25 % from rice cultivation, 16 % from oil/gas extraction, 16 % from refuse)	270
Sulfur dioxide	77
Dinitrogen oxide	13

3. WASTE ENERGY AND ENTROPY EXPORT

As noted before, a qualification of waste energy is based on the entropy law. Real systems are mostly open systems. They do not only exchange energy with their environment as do closed systems, but simultaneously exchange mass. Via mass and energy transfer with the environment they export entropy. If this export is higher than the entropy production due to natural processes inside the system, then the entropy of the system is reduced. A lower entropy is, however, equivalent to a higher state of order as in the environment. Such a state is characteristic for higher structured systems, in contrast to systems in an unstructured state where, for example, all potentials are balanced out and the system has reached an entropy maximum. Through this statement, which says that a higher structuring can only be achieved in open systems, Prigogine [1] cleared the former inconsistency in the entropy law, according to which potential differences balance out until equilibrium is reached so that processes end, which seemed to be in contrast to the fact that higher structured systems are built up during evolution.

Our planet Earth in this sense is an open system. All energy irradiated from the Sun is again emitted into the Universe. However, whereas the surface temperature of the Sun is equivalent to that of a black body of around 5 800 K irradiating energy to the Earth, the same amount of energy is emitted at around 300 K, the temperature of the earthen atmosphere. The irradiated heat flux $\dot{Q}_i$ is equal to emitted heat flux $\dot{Q}_e$

$$\dot{Q}_i = \dot{Q}_e$$

or

$$T_i \Delta S_i = T_e \Delta S_e$$

Therefrom

$$\frac{\Delta S_i}{\Delta S_e} = \frac{T_i}{T_e} = \frac{5\,800 \text{ K}}{300 \text{ K}} = 19.33$$

The entropy export ΔS_e is about 20 times higher than the entropy import. It is true that the large difference comes from the entropy production due to natural processes on the Earth, but it also enables the formation of higher structured systems and particularly the emergence of life.

This interpretation can also be applied to subsystems on earth. They are open systems, as well, and the energy and mass transfer with their environment in connection with the entropy export promote to establish or maintain structures, respectively a state of order within the system, and the entropy export of technological systems permits establishing or maintaining a state of higher order than that of the environment. A higher order, on the other hand, means a lower entropy level and potential differences towards the environment.

The entropy export is realised through the emission of heat and mass, in other words, through the emission of fluxes consisting mostly of waste energy and waste products. Thus, the waste energy appears in a different view: as an entropy carrier it helps to maintain or establish the state of order within the system.

This statement has manifold consequences. If the parameters of substances needed for a process or removed from it are different from the state of environment, the technological system has to undergo an entropy export due to the external irreversibilities. A reduction of the amount of those substances, for instance, by refuse recycling, may then require a higher entropy export. In other words: refuse recycling requires energy and thus leads to a pollution of the environment, which partly or fully ruins the benefits made by saving material. Material recycling and waste energy recovery should, therefore, be considered under the same aspect, for instance, via entropy considerations, in order to avoid contradictory tendencies. An essential aim of an entropy-based economy should be the reduction of entropy increase in processes and the external irreversibilities, and thereby the approach to reversibility. By this, not only the mass and energy transfer and damage done to the environment is reduced, but also less primary energy is needed. The goals of an entropy-based economy, thus, are in agreement with a sustainable development, and with the aid of the entropy, processes and their effect on the environment can be assessed quantitatively.

3.1. A review of energy and entropy export

Some numbers illustrating the energy and entropy export are given in *table III*. The entropy export in this table is calculated by dividing the energy through the temperature 300 K of the environment, the average temperature of

TABLE III
Energy and entropy export.

Species/system/process	Energy export into environment in W	Entropy export into environment in $W \cdot K^{-1}$
Total export from Earth	$178 \cdot 10^{15a}$	$0.6 \cdot 10^{15}$
All power stations	$2.4–3 \cdot 10^{12b}$	$0.8–1.0 \cdot 10^{10}$
Domestic heating	$2.4–3 \cdot 10^{12}$	$0.8–1.0 \cdot 10^{10}$
Rusting of iron	$1.2 \cdot 10^{12}$	$4 \cdot 10^{9c}$
All human beings (body temperature 37 °C)	$0.9 \cdot 10^{12}$	$3 \cdot 10^{9}$
Fumes and exhaust gases	$0.6–0.9 \cdot 10^{12}$	$2–3 \cdot 10^{9}$
Single human being (body temperature 37 °C)	150	0.5
Countries:		
All countries	$12 \cdot 10^{12}$	$4 \cdot 10^{10}$
USA	$2.7 \cdot 10^{12}$	$9 \cdot 10^{9}$
Germany	$0.43 \cdot 10^{12}$	$1.4 \cdot 10^{9}$
India	$0.43 \cdot 10^{12}$	$1.4 \cdot 10^{9}$
France	$0.32 \cdot 10^{12}$	$1 \cdot 10^{9}$
UK	$0.32 \cdot 10^{12}$	$1 \cdot 10^{9}$
Italy	$0.25 \cdot 10^{12}$	$0.8 \cdot 10^{9}$

[a] 10^{15} W = 1 PW (Petawatt).
[b] 10^{12} W = 1 TW (Terawatt).
[c] 10^{9} W = 1 GW (Gigawatt).

energy export into the environment. Although the numbers in *table III* are approximate numbers, they reveal some interesting facts. The entropy export from the Earth of $0.6{\cdot}10^{15}$ W$\cdot$K^{-1} or 0.6 PW$\cdot$K^{-1} is equivalent to a specific entropy export of around 1.2 W$\cdot$K$^{-1}\cdot$m^{-2}, the Earth surface being $5.1{\cdot}10^{14}$ m^2. The total energy consumption of the humanity $12{\cdot}10^{12}$ W is equivalent to an entropy export of $4{\cdot}10^{10}$ W$\cdot$K^{-1} or, if divided by the earth population of $6{\cdot}10^9$ persons, of 6.6 W$\cdot$K^{-1} per person. It is roughly spoken about 15 times higher than the entropy export of a single human being of 0.5 W$\cdot$K^{-1} necessary to maintain a body temperature of 37 °C.

As we can see the entropy export of all power stations with 0.8–$1.0{\cdot}10^{10}$ W$\cdot$K^{-1} = 8–10 GW$\cdot$K^{-1} is of the same order of magnitude as for domestic heating. The entropy export of hot fumes and exhaust gases is of the order of 2–$3{\cdot}10^9$ W$\cdot$K^{-1} = 2–3 GW$\cdot$K^{-1}. It is noteworthy that the different composition of these gases as well as the difference between exhaust state and state of the environment also cause an entropy export. Because of the different partial pressures of the exhaust gases and the same gases in the ambient air we notice a high entropy export of the order of $1.5{\cdot}10^9$ W$\cdot$K^{-1} = 1.5 GW$\cdot$K^{-1}. It is also interesting to note that energy consumption and entropy export of India and Germany are almost the same, though the population of India with its almost 1 000 millions of inhabitants is more than the 12-fold of that of Germany with its 80 millions of inhabitants.

4. OPTIONS FOR WASTE ENERGY UTILISATION

The previous numbers clearly indicate the quantitative importance of waste energy. They also reveal what causes large entropy exports and, thus, give hints for measures to reduce losses. Therefrom priorities for the different measures can be derived, and this cannot be done alone on the basis of energy balances.

Although detailed technical problems and their solutions are discussed in the following papers [2–5] a few general remarks shall be given here.

If we consider external irreversibilities, for instance, due to waste energy, the goal has to involve the final discharge of all flows after processing into the environment, in a state, whenever possible, close to equilibrium with the environment. Therefore, energy cascades are to be striven for. They are supported in a closer sense, for example, by the use of industrial waste heat for domestic heating or by a wider use of co-generation for the simultaneous supply of heat and electric consumers. In addition to this, technically well developed proposals exist that could be realised on the basis of a network of integrated systems, especially from heat and district heating networks.

The appropriate development in the regenerative use of heat, which have a significant importance with regard to quality, are being restricted in industry through the loss of useful temperature levels, because most often the focus is placed on product-oriented essential sectors. The dominance of chemical processing and production in the structuring of industrial processes suppresses the significance of structuring according to the principles of energy cascades and thereby, in principle, of rational energy use and of entropy economics. Certain exceptions are the fundamental processes of food industries, as well as specialised areas of chemical, energy, and waste disposal industries, examples are petroleum refineries and thermal process industries.

Of very high importance in such studies is the process of heat transfer, which, as it is well known, is responsible for large entropy production in economics and society. A possible solution to situations where heat cascades are not applicable is offered by the integration of heat transformation processes of various kinds. Because of these, unoccupied or unavailable levels of temperature for energy use can be bridged through circuit processes, integrated into the process, placed before or after the process. The technical possibilities for these processes are well known to exist in the entire capacity range, from a few kW to some MW. Due to liberalisation of the energy market for electrical energy, the option of implementing such processes appears to be gaining importance. With this, close link-ups of production processes and reciprocal dependencies, which require safety devices and corresponding reserve circuits, can be avoided.

In conjunction with the evaluation of the possibilities in the gas industry it has to be mentioned that the combustion process, apart from heat transfer, is likewise through its irreversible direction one of the biggest sources of loss in the entire supply of energy. The present technology of gas usage means that combustion processes are further-on contemporary technologies, and because of this no new level of quality is being attained from a thermodynamic view in comparison with other sources of energy. This is only possible in conjunction with the use of fuel cells. In light of the strong impact of heat transfer and combustion processes, methods such as fuel cells and various forms of sorption and thermochemical cycles appear to be of special significance. A great deal of attention should therefore be devoted to these in research.

Especially close connections exist between energy and chemical industries in the reprocessing and use of waste and also in the supply and use of biomasses. It has been well established that chemical energy from waste can be converted up to 80 % into thermal energy with current methods. If only substances are recycled the chemical energy is preserved, the process requires, however, the use of energy. These interrelations as an alternative to purely energetic methods, i.e. in connection to complete chemical recycling, have to be taken into consideration.

The use of biomass as a source of energy can be, for example, in rural regions, an interesting solution for all sorts of reasons and of course not only for those concerning energy. The material structure of biomasses as energy sources, in comparison with fossil fuels, from an entropic point of view have some characteristics, such as high humidity, high oxygen content and, thus, a high entropy of reaction. As reversibility cannot be achieved by the usual combustion processes, the high entropy of reaction should be determinedly used in gasification reactions in connection with a heat input from the environment. Otherwise, the implementation of these sources of energy are primarily associated with logistic problems.

Summarised, it has to be maintained that from a technical point of view a variety and number of possibilities are known useful for a reduction and utilisation of waste energy. They contribute to a reduction of energy usage and are, due to the quantitative importance of the energy industry, a fundamental contribution to a sustainable development. However, their usage is being limited if not alltogether obstructed by a wide range of social conditions. In order to follow these connections it is necessary to start, on the one hand, from general considerations of the concrete requirements of usage.

5. CONCLUSIONS

Waste energy, different from primary energy, is of low quality. Nevertheless, because of the tremendous amount of waste energy polluting our environment, a reduction or better utilisation of waste energy not only reduces the ecological damages but also helps to save primary energy. As discussed in this paper, with the aid of an entropy-based assessment, strategies for a better waste energy utilisation or reduction can be developed.

In order to reduce the external irreversibilities discharges of waste energy into the environment should, whenever possible, be close to equilibrium with the environment. As a consequence, energy cascades should be striven for. They can be supported, for instance, by heat transformation integrated into industrial processes, by the use of industrial waste heat for domestic heating or by the simultaneous supply of heat and electricity by cogeneration processes.

With the aid of heat transformers integrated into the processes unoccupied or unavailable levels of energy use can be bridged.

The present technology of gas usage in combustion processes with their high entropy production requires a great deal of attention to be devoted in research and development of fuel cells and the various forms of sorption processes.

Although there exist at present a great variety of options and possibilities for a better use of waste energy, each specific situation requires its special solution taking into account not only the technical, but also the economical, social and legal conditions and implications. By doing that one should avoid drawing one-dimensional and, therefore, only partially valid conclusions from general statements, which often lead to unproductive discussions.

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