THE VALUE OF ENERGY CARRIERS

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Abstract—The value of energy carriers can be described thermodynamically by the amount of heat (enthalpy method) or work (exergy or availability method) that can be obtained from the carriers. Prices for energy carriers are used in economics to express their values. The prices for energy carriers are often related to their enthalpies when other properties and conditions are equivalent. However, it has been suggested that the exergy of the energy carriers is the proper quantity to establish their values, i.e. prices should be based on these exergies.

In this paper, the structure of the energy demand is included in the analysis of the value concepts. The aggregated energy demands of the industries in The Netherlands and West Germany (F.R.G.) are used as examples. Optimization of the total system is the proper way to establish the performance of energy carriers. In this optimization, several assumptions must be made about availability and applicability of technical options, such as heat cascading, cogeneration and heat pumps. The structure of the demand influences the importance of energy carriers and thus their value in a given system. Neither the enthalpy nor the exergy of the energy carriers is an adequate base for price setting.

INTRODUCTION

Energy is available in nature in many different forms; by applying conversion technologies, other forms can be obtained. There are several reasons for comparing different energy carriers in their power to create a change in systems. For this purpose, it is necessary to allocate a number to the energy carrier describing the goodness or the value of the energy carrier.

There are at least three different methods in use to arrive at a value of the quality of the energy carriers: (1) The amount of heat that can be obtained from the carrier by some conversion method. This method is used in the official energy statistics of nations and in many other applications (enthalpy method). (2) The amount of high quality work that can be obtained from the energy carrier when an ideal conversion device exists (exergy or availability method). (3) The price that is being paid in the economic system for the energy carrier (economic method).

The subject of the valuation of energy carriers has received much attention in recent years and the results of these activities are summarized in the next section. In spite of progress in the theory, some major questions remain to be solved. Should pricing be based on the exergy of the energy carrier? Should statistics be based on exergy or should we continue the use of enthalpy for this purpose? Can we measure the energy productivity of industrial processes and can we register changes in this productivity caused by conservation programs?

We analyze the suggestion to base energy pricing on exergy of the energy carrier. The influence of the structure of the demand will be investigated, since in some simple demand situations the suggested pricing system is not adequate. To facilitate the discussion of more complex situations, a diagram is developed showing both the enthalpy and the exergy descriptions of supply and demand.

ENTHALPY, EXERGY AND PRICES

The physical description of what can be done with energy has its roots in thermodynamics. Some results of this theory are used, but we refer for detailed aspects to the literature.[1-4]

Nearly all energy resources can be used to produce heat, either by natural processes (such as solar energy falling upon the desert) or by technical means, such as burning coal

in a furnace. Since the major part of the world energy use is based on making heat by burning fossil fuels, energy statistics are generally formulated in terms of the power of fuels to produce heat. Thermodynamics describes this heat under certain conditions through the concept of enthalpy.

There are problems with using the heat concept in describing the value of energy carriers. Some primary energy resources, such as water power and uranium, cannot be burned to produce heat. Gardel has analyzed this problem in great detail.[5] Furthermore, electricity plays an important role in society, but by taking the heat equivalent of electricity its value would be presented very inadequately. Official statistics recognize this fact by using a separate electricity balance. A problem is that heat as such is an insufficient characterization of the value of heat: heat of say 1000 K has greater value than heat at 300 K. The concept of value refers to the amount of high-quality work, such as electrical energy or mechanical energy, that can be obtained from an energy carrier when the proper conversion device exists. This amount of high-quality work is thermodynamically described as exergy or availability.

Details concerning the actual calculation of enthalpy and exergy of materials, mixtures, and processes have been discussed.[4,6–8] For fossil fuels, the differences are limited but as soon as heat, especially low temperature heat, plays a role, important differences occur in values and in interpretation. Even when heat is produced with 90% enthalpy efficiency, the exergy efficiency may be as low as 10%. Many operations in society occur with a low exergy efficiency.[9]

Since heat at different temperatures is used in the following discussion, aspects of the reference state must be mentioned here. Experimentally, differences of thermodynamic quantities between states are measured and one uses a set of reference states in order to attach values for these quantites to states. Generally, pure compounds at 298.15 K under a pressure of 101.3 kPa (1 atm) are used as reference. In exergy calculations, we want to know the maximum amount of work that may be obtained when fuels are burned under practical conditions. Then nature is used as reference state. All waste heat disappears in the environmental reservoir, which is assumed to be at 298.15 K. This approach places heat in a special position with respect to the chemicals used in the processes: they return to a dead state. For heat, the dead state would be 0 K. It is easily demonstrated that, when heat goes from a high temperature T_1 to a lower temperature T_2, the maximum amount of high quality work that can be obtained is given by the fraction $1 - (T_2/T_1)$, which is the Carnot factor and will be used here to describe the quality of heat (see also the Appendix). In summary, the enthalpy method refers to heat amounts, whereas the exergy method represents the possibility to produce high-quality work. This is the reason for the proposal[10–13] to use exergy values for the pricing of energy carriers: performing high-quality work is considered to be the essential function of energy, not the production of heat.

This interpretation of the value of energy in society includes a value judgment: energy shall be used in such a manner as to induce the largest changes in some acceptor system. But what happens when society needs only small changes on a large scale, such as the heating of buildings and homes?

DIAGRAM OF SUPPLY, DEMAND, AMOUNT AND QUALITY

It is useful theoretically to describe energy-conversion processes as the interaction of an energy donor with an energy-accepting system. This interpretation can be used not only for the overall process, but it is also true for steps on a molecular scale. This approach has been described earlier.[14] In complex energy systems, the same approximation is followed.

It is assumed that all supplies (primary and secondary energy carriers) and all needs (secondary energy carriers and the final energy function) are available as continuous flows at one location. Thus, energy storage and energy transport are neglected. The theory is not a pure academic exercise because of these restrictions, since industrial flow processes

and industrial complexes are often analyzed for these conditions.

The amounts of energy in the enthalpy description can be summed for the donors and acceptors, leading to the enthalpy efficiency of the operation. However, information about the quality is lost in this procedure. For this reason, it is useful to introduce the concept of quality of the different needs and supplies as follows:

$$\text{quality} = Q = (\text{amount of exergy})/(\text{amount of enthalpy}) = (\Delta B)/(-\Delta H). \tag{1}$$

It is understood that the amounts are theoretical maxima for the donor process and theoretical minima for the function to be fulfilled in the acceptor process. Thermodynamics shows that

$$\Delta B = -\Delta H + T_0 * \Delta S, \tag{2}$$

where ΔS is the entropy change of the process by which the exergy of energy carriers or of final energy functions is established and T_0 is the absolute temperature of the general heat reservoir (298.15 K). Thus,

$$Q = 1 + T_0 * \Delta S/(-\Delta H). \tag{3}$$

Several situations are important: (a) For some forms of high-quality energy (e.g. mechanical and electrical energy), no entropy change is involved and thus $Q = 1$. (b) The processes used to evaluate the exergy of chemical energy carriers do not necessarily have a zero entropy change. Thus, ΔS can be larger than one (this happens when the number

Table 1. Quality Q of some energy carriers

Heat			Q
K	°C	°F	
298	25	77	0.00
363	90	158	0.18
398	125	257	0.25
993	720	1320	0.70
2982	2705	4901	0.90

Chemical energy[†] at 298.15 K	$-\Delta H$ (kJ/mol)	ΔS (J/(mol*K))	Q
Methane (HHV)	890.9	−242.6	0.92
Methane (LHV)	802.7	−5.0	1.00
Carbon	393.7	3.0	1.00
Hydrogen (HHV)	286.0	−163.1	0.83
Hydrogen (HLV)	241.9	−228.7	0.98
Butane (HHV)	2880.1	−437.8	0.95
Butane (LHV)	2659.6	156.2	1.03

† The data were obtained with programs available from the authors. The results are close to what has been calculated with the best available data elsewhere.[3]

of gas molecules in the processes increases) and consequently the quality may be greater than one. Generally, Q does not differ greatly from one for fossil fuels, as is illustrated in Table 1. When heat is available as a continuous flow at a temperature T (Kelvin), the maximum amount of work with $Q = 1$ that can be obtained is given by the Carnot factor

$$Q = 1 - (T_0/T). \tag{4}$$

When a batch at temperature T is cooled down to the reference temperature, another formula[5,8] must be used. Some quality values for heat are collected in Table 1.

It is possible to plot the amounts of both demand and supply $(-\Delta H)$ as a function of the quality Q. Here, the energy amounts are plotted with arrows, as a symbolic representation of the Dirac-delta functions. These diagrams will be indicated as HQSD-diagrams, since enthalpy (H), quality (Q) as a measure for the corresponding amount of

exergy, supply (S), and demand (D) are all presented in this diagram. The word virtue has been used in the literature for what is called here quality.[16,17] Although the concepts are equivalent, the graphical presentation is different from the method used in this paper. Quality according to our interpretation occurred in other energy conservation studies.[18]

The HQSD-diagrams are useful to illustrate aspects of energy-conversion processes. Energy donation is presented with arrows up when energy with one well-defined quality value is used; the energy-accepting action is presented with arrows down. The amount (ΔH) times the quality presents the exergy involved. In a conversion process, the total amount of exergy used to fulfill demand can not be larger than the amount of exergy donated. Given a demand pattern (the accepting system), we may calculate the minimum amount of exergy necessary to meet this demand. Comparing this demand with the actual amount of exergy used under practical conditions, we obtain the exergy-efficiency of the process.
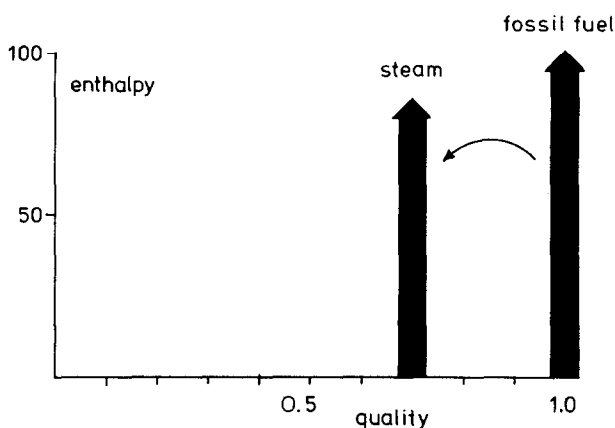

Fig. 1.   Steam production from fossil fuels.

In Fig. 1, the situation is sketched when fossil fuels with an approximate quality of unity are burned and the heat is converted into high-pressure and high-temperature steam. This process may occur with 90% enthalpy-efficiency, but the quality of the steam is below 0.7, as has been shown in the literature.[5,9] Thus, once steam has been made, at least 37% of the originally available exergy is lost. In actual applications, we do not use steam to meet demands above $Q = 0.6$.

The burning of fossil fuels followed by the production of steam constitutes a major application in electricity production and in the heat-requiring industry. In electricity production, steam is used for the production of electricity with $Q = 1$, together with a large amount of heat with a very low quality (Fig. 2). In modern utilities, electricity is produced at 40% enthalpy- or exergy-efficiency with respect to the used fuels or at 63% with respect to the intermediate steam. These are very high exergy efficiencies compared to those reached in other industrial processes. Since enthalpy can not be lost, the remaining 60% occurs as waste heat with a very low exergetic value.

SUPPLY OPTIMIZATION FOR COMPLEX DEMAND PATTERN

The objective is to study the value of energy carriers by means of optimization of the supply in complex demand situations, such as chemical processes or larger industrial complexes. In these situations, many heat requirements exist on different levels. When it is assumed that in many applications the function of the demand at a certain quality value is just to keep, for example, materials or goods for some time at the temperature level corresponding to that quality, a part of the heat may be available for use at a lower quality. This consideration leads to the possibility of heat cascading. The re-use flows are described as hot streams. Other forms to manipulate heat may be available. The heat pump uses
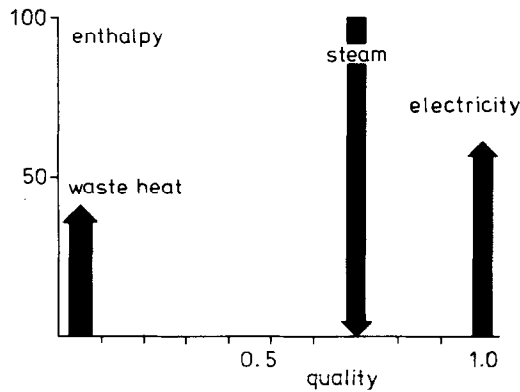
Fig. 2. Electricity production from steam.

electricity to upgrade heat. Cogeneration is used when both electricity and low-quality heat are required. In addition to a high-quality fossil fuel, other low quality energy carriers may be available, for example, geothermal heat. The system has many options, since one or more of the technical options (heat exchangers, cogeneration, heat pump, low-quality energy carriers) might not be available. Optimization calculations are described elsewhere[20] but some preliminary results are used here for illustration. The following problem has been studied by Linnhoff and Flower in detail,[21,22] using enthalpy–temperature diagrams. The subject is important, since heat integration is the major option for increasing the energy productivity in industry. Although there are practical differences between the method of Linnhoff and Flower and the method used by us, the two approaches lead to similar results with respect to the use of cogeneration and heat pumps.

For illustration, we use the integrated heat demand of industry. There is the problem of the available statistics. For the F.R.G. and The Netherlands, the structure of the industrial heat capacity demand is roughly known.[23,24] The electricity demand of industry has been added to the available heat data. For several reasons, high accuracy should not be attached to these data. It is known, for example, that the large heat requirement for low Q-values in the Dutch situation has been reduced considerably by conservation measures.

The plot of enthalpy vs T can be converted to a plot of enthalpy vs Q by using

$$\Delta H_i(Q) = C(T)*\Delta T, \quad Q = 1 - (T_0/T), \quad \Delta Q = T_0*\Delta T/\ T^2. \tag{5}$$

Here, ΔQ and ΔT are corresponding and $C(T)$ is the (average) heat-capacity demand in the range ΔT according to Fig. 3.

The demand sketched in Figs. 3 and 4 can be met by using a fossil fuel with quality 1. It assumed that this process occurs with an efficiency of 85%. Next, it is assumed that 90% of the heat used at a certain level becomes available for use at lower levels. It may happen that too much enthalpy is available due to heat cascading: this result is shown in Table 2 as EXCESS. The levels are indicated by $D = 10*Q$. The electricity demand is shown on level 10. It is assumed that electricity is produced from the fossil fuel with 40% efficiency.

Important is the level where the excess is zero. It corresponds to the pinch in the theory of Linnhoff and Flower: below the pinch, no direct heat input is required.

The amount of primary energy can be calculated for the two situations. The results are summarized in Table 3.

The situations with and without heat cascading are extremes. Without heat exchangers, all of the heat at a particular quality level may be required and no waste heat is available for heat cascading. This type of behavior occurs in chemical processes when endothermic reactions take place. The description is certainly not true for all industrial energy use.
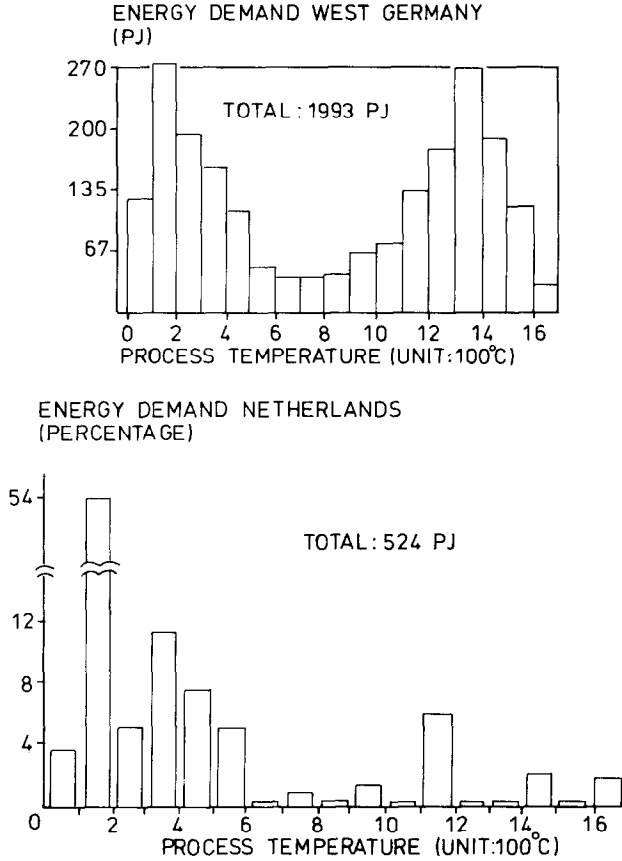
ENERGY DEMAND WEST GERMANY
(PJ)

TOTAL : 1993 PJ

PROCESS TEMPERATURE (UNIT:100°C)

ENERGY DEMAND NETHERLANDS
(PERCENTAGE)

TOTAL: 524 PJ

PROCESS TEMPERATURE (UNIT:100°C)

Fig. 3. Industrial heat capacity demand in West Germany and The Netherlands.

× 10 PJ
enthalpy
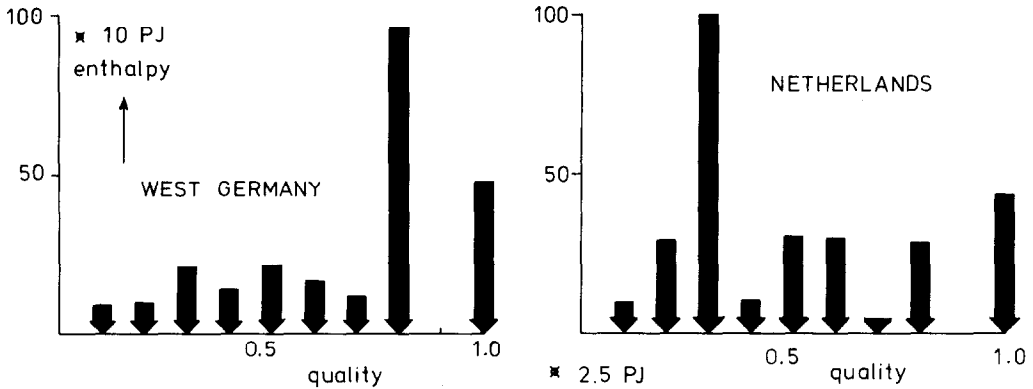
WEST GERMANY

quality

NETHERLANDS

× 2.5 PJ

quality

Fig. 4. $H - Q$ diagram for West Germany and The Netherlands (electricity demand added at $Q = 1$).

There are many processes, which require high temperature in order to run sufficiently fast. They may not need an energy input and, in some cases, additional energy is even obtained. The second case, with heat cascading on all levels, is also extreme in the sense that all demands are supposed to be available for reuse with 10% loss in enthalpy and 0.1 loss in quality. The real situation is somewhere between these two extremes and further data are required to analyze different demands.

We must keep in mind that the demands, as used here, do not give any indication about process efficiency. Energy conservation in the industry has been studied extensively (see, for examples Refs. 18 and 22). We deal with the efficiency of the supply system and integration of the supply system with demand, which is important, when prices of the

Table 2. Fulfillment of energy demand (heat cascading available)

The Netherlands	Level	Demand	Direct energy	Excess
	1	23	0	198
	2	72	0	156
	3	253	181	0
	4	24	0	50
	5	75	0	7
	6	74	0	15
	7	9	0	81
	8	70	0	27
	9	0	0	97
(Electricity)	10	108	108	0
West Germany	1	93	0	673
	2	100	0	676
	3	207	0	590
	4	137	0	674
	5	218	0	614
	6	161	0	687
	7	120	0	740
	8	956	524	0
	9	0	0	432
(Electricity)	10	480	480	0

Table 3. Required enthalpy and energy (in PJ)

	The Netherlands	West Germany
Enthalpy demand $= \sum_{D=1}^{10} H(D)$	708	2473
Exergy demand $= \sum_{D=1}^{10} 0.1*D*H(D)$	354	1681
Fuel required (Enthalpy $=$ Exergy)		
Without heat cascading	976	3544
With heat cascading	483	1816

intermediate supplies are considered with heat cascading. It must generally be assumed that energy becoming available at level $D - 1$, after use at level D, has to be sold on the energy market. When it could have been used by the owner of the plant with demand D, it should have been used in the plant itself to decrease demands at lower levels.

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Returning to the value problem, the following conclusions can be obtained from the calculated data.

It often happens that a single fuel, such as oil, is used to drive the plant, the complex or even the country. When several fuels with quality $Q = 1$ are used, they may be lumped together, as was done in the calculations for Tables 2 and 3. Then there is no difference between enthalpy and exergy calculations. Optimization shows the lowest amount of fuel required theoretically. The values of the energy carriers are equivalent and their price setting is identical, whether enthalpy or exergy is used as basis.

However, when several inputs are used or when several energy outputs are obtained simultaneously, the value problem becomes more interesting. We assume, for example, that another resource with quality 0.3 is available. In the Dutch situation, we can use this resource to meet the direct energy on level 3 (181 PJ). The total exergy input into the system decreases by this substitution. According to the suggestions mentioned earlier, the low-quality resource should be priced 0.3 times the price of the high-quality resource. Economically, however, any price lower than the price of the high-quality carrier would be sufficient for the switch. In the F.R.G., there is no need at all for direct energy input at the lower levels. Consequently, both the physical and economic values of the low quality fuel are zero.

This example shows that the physical and the economic values of energy carriers are influenced by the structure of the demand, by the availability of technical options, and by the way the economic optimization works.

CONCLUSIONS

It is possible to define the enthalpy and exergy of energy carriers and to optimize complex demand and supply interactions. Enthalpy and exergy optimization do not necessarily lead to the same result. The contribution of each carrier may be established and thus its value under optimization. The result depends on the structure of the demand and other factors, which means that an energy carrier may be valuable in one situation and worthless in another. Thus, it is not possible to establish values for the energy carriers that will be generally meaningful. There is no single physical property (including exergy) that can be used as a base for the economic price of energy carriers. The interaction between energy analysis and economic evaluation is further complicated by the fact that the availability of technical options which influence energy optimization may be excluded economically because of investment cost. Other factors will change the final outcome of the optimization. A complete analysis must deal with the trade-off between energy, environment and economic values.[25]

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APPENDIX

Carnot Factor

In Fig. A1, the number of particles is given as a function of the energy for two temperatures. In the transition from high to low temperature, we expect a conversion into work from the particles of the non-overlapping part when the proper device is available. In Fig. A2, the corresponding energy is plotted. The transition from area I
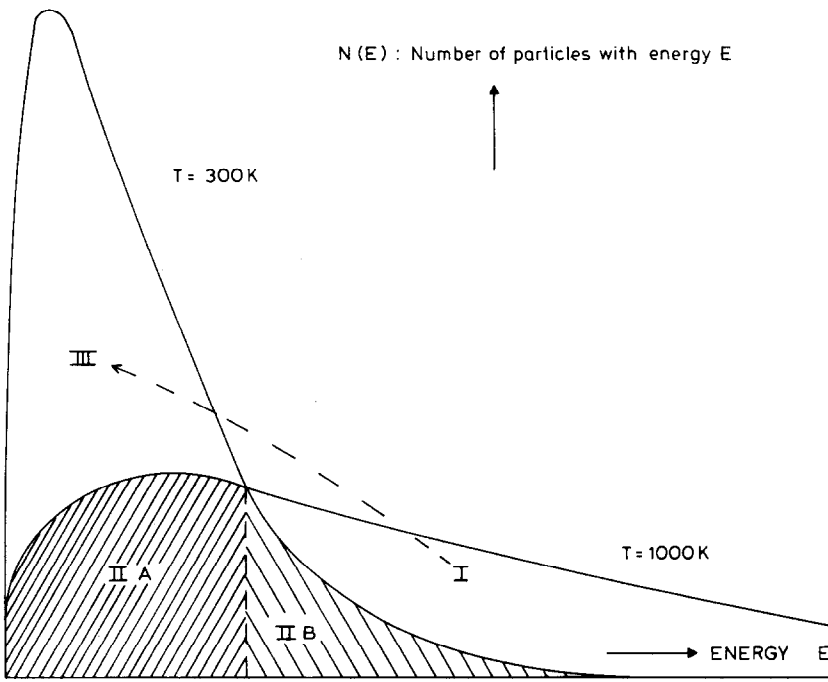
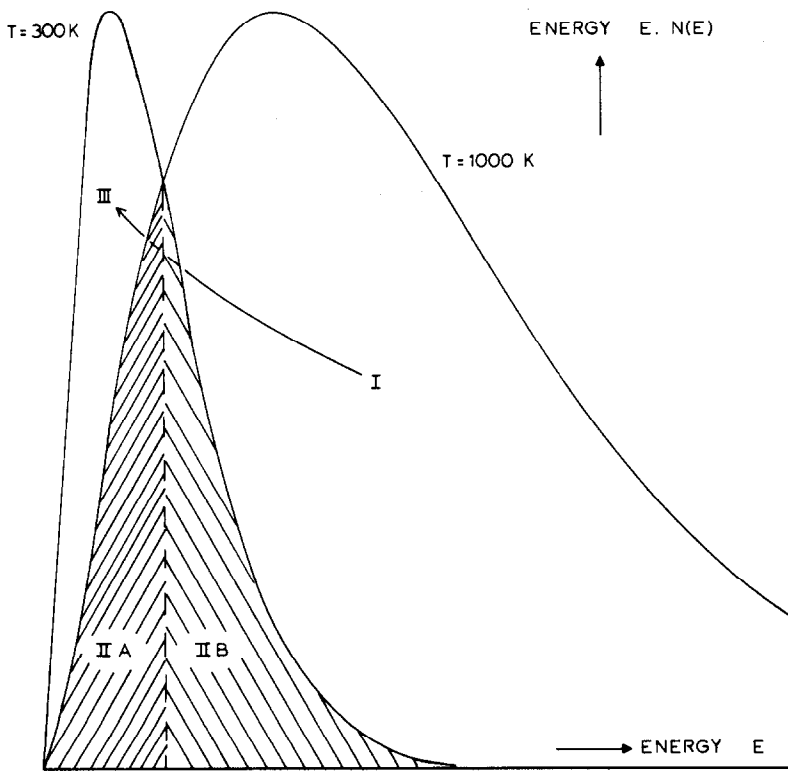Fig. A1. Number of particles as function of the energy (ideal gas).

Fig. A2. Energy available for conversion follows from the transition I → III.

to area III corresponds to the following energies:

$$E_I - E_{III} = (E_I + II_A + II_B) - (E_{III} + II_A + II_B) = E_{1000} - E_{300} = 1.5 * N * k (T_1 - T_2),$$

where N the number of particles and k the Boltzmann constant. The energy from the 1000 K gas is basically available, corresponding to $1.5 * N * k * T_1$. The ratio between what can be obtained as work and what is available is the Carnot factor $1 - (T_2 / T_1)$. The restriction in the conversion efficiency, as given by the Carnot factor does not originate from the fact that we are dealing with heat but is due to the use of the non-zero reference state given by the low temperature reservoir.