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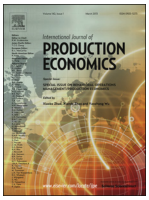

On the true value of resource consumption when using energy in industrial and other processes

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ABSTRACT

In this paper we attempt to provide a partial answer to the question of why energy is a scarce resource. Scarcity is a fundamental concept in the science of economics. If resources, goods or services were not in scarce supply, we need not economise when utilising them. Indeed, free commodities we need not pay for, their prices are zero, we attach no economic value to them, and their supply is in abundance – at least beyond the point at which our needs and wants are satisfied. However, energy is regarded as a scarce resource, although energy – as such – is not scarce. To describe energy as a useful and therefore a valuable quantity, to which a price may be attached, energy will thus have to be characterised in further dimensions than energy content alone. Apart from quantity, there is a need for a uniform qualitative measure of energy. The obvious field to revert to for such considerations is *thermodynamics*, which offers a method for defining a uniform measure for the qualitative content of energy, namely *exergy*.

Although exergy is defined from purely physical properties, it is shown to have an important rôle to play when comparing the economic value of energy in different forms. In particular, this paper will focus on the economic value of heat, especially heat delivered through a district heating system.

The concept of exergy is defined from maximising a work output reversibly taking an infinite time. However, for processes to run within finite horizons, entropy must be generated. This leads us to add finite time considerations from examining consequences from the assumed availability of so-called endo-reversible processes.

In a small case example we show that heat appears to be overpriced compared to electricity from an exergetic point of view and that this is even more pronounced adopting finite time considerations.

1. Introduction

Energy as a resource is treated in a very simplistic way in today's debate on resource utilisation. It seems often as if the general public views energy as coming in lorries carrying petrol or other substances. According to the author, this is not so. Resources come with lorries or in pipelines, but not the kind of energy that is the resource. The resource that is demanded on the market is the ability to carry out work, i.e. lifting a weight, moving a vehicle against friction, etc.

Energy, as such is in abundance, in particular in consideration of the Einsteinian equivalence between matter and energy $E = mc^2$, where E is energy, m is mass and c the velocity of light in vacuum. Essentially everything is energy, so it cannot be scarce, and therefore it cannot be a resource on which we must economise. The economic value of an abundant resource would be zero. The scarcity of energy must therefore be found in other properties than in the extensive property of energy content alone.

A norm for the comparison of energy in different forms was coined as *exergy* by the Slovenian scientist Zoran Rant (1904–1972) in 1956 (Rant, 1956). Similar concepts had been in place a long time before, such as *availability* or *available energy* (*technische Arbeitsfähigkeit* in German). In some cases availability is still the preferred term, cf. (Kline, 1999).

Exergy is defined as the amount of mechanical work that energy in a certain form (such as heat) may be transformed into when objects interact. When energy is used (it is indestructible and never destroyed), its exergetic content is lowered, and exergy is consumed. The amount of exergy that an amount of heat corresponds to, depends in particular on its own temperature together with the temperature of the ambient.

In several domestic and industrial applications, energy is used having a lower grade than its exergetic content. For example, district heating has been available in many cities around the world for several decades for warming space and heating water. The main way, in which its volume of use has been measured, has been *the amount of heat* taken from the district heating network to feed domestic heating equipment. The cumulative amount of heat,

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together with the cumulative flow of the medium (normally hot water) and the "capacity" (power level) required, have been the main determinants for the heat "consumption" that the domestic or industrial user has been charged for.

It is common in practice that heat is directly compared with electrical energy. Amounts of heat taken from the network have often been compared in price per kWh to the price of electricity in the same physical and economic units. However, heat and electricity are indeed very different. By way of example, electricity feeding a light bulb produces light, but the same amount of heat energy (at a finite temperature) cannot produce the same lighting. If located in a space that needs warming, the light bulb creates light as well as waste heat, the latter immediately recycled at no additional cost for heating purposes. Electricity is therefore technically superior. In this case, electricity thus provides two services, but not heat.

There is an increasing awareness that a sustainable development of society requires that energy resource utilisation is measured according to objective scientific principles in which the concept of exergy plays a central rôle. One simple argument illustrating this is given by the example from Rosen et al. (2008).

> To increase the utilization of more environmentally benign and sustainable energy and technologies, the benefits that they bring must be clearly understood and appreciated by experts and non-experts alike. The latter category includes the public, the media and decision makers in industry and government.
>
> Consider a geothermal power plant using geothermal liquid water at 160 °C at a rate of 440 kg/s as the heat source, and producing 15 MW of net power in an environment at 25 °C. Energy analysis allows us to determine that this source has an energy value of 251 MW and the energy efficiency of the plant is 6% (15/251 MW). Exergy analysis shows that the source has a work potential (i.e., exergy) of 44.5 MW and the plant exergy efficiency is 34% (15/44.5 MW). Here, the exergy of geothermal water constitutes only 18% of its energy. The remaining 82% is not available for conversion to electricity, even with a reversible heat engine. Only 34% of the exergy entering the plant is converted to electricity and the remaining 66% is lost. An exergy analysis of this plant also identifies the sites of exergy losses in a quantitative manner and helps in prioritizing improvement efforts. Clearly, these insights to the plant operation cannot be attained by an energy analysis alone. The low value of energy efficiency here is misleading as the maximum energy efficiency of this plant is limited by its Carnot efficiency whose value in this case is 0.31 = (1–298 K/433 K).

2. The exergy concept

Exergy has been defined as the amount of *mechanical work* that can be obtained from letting an object interact with an infinitely extended stable environment, cf. (Baehr, 1965; Ford et al., 1975; Eriksson et al., 1978; Wall, 1986, Shukuya and Hammache, 2002; Gaggioli et al., 2002; Gaggioli and Paulus, 2002). The object is defined with co-ordinates describing its thermodynamic properties, and so is the environment.

Thermodynamic properties are of two kinds, *extensive* and *intensive*. Extensive properties are mass, volume, entropy, and similar, and intensive properties are temperature, pressure, chemical potentials, etc. *Entropy* plays a special rôle among the extensive properties, since the total of entropy is not necessarily conserved, whereas totals of other extensive properties are. Indeed, the *second law of thermodynamics* states that total entropy of a system of objects (including an environment) may never decrease.

A basic property (also extensive) of an object is its *internal energy* U. Internal energy is the intrinsic energy embedded in an object. *Gibbs' fundamental equation* (Gibbs, 1876, 1878) states that U is a linearly homogeneous function of the object's extensive properties. If $\mathbf{x}$ is a vector describing these extensive properties, this means that $U(k\mathbf{x})=k\,U(\mathbf{x})$, where k is any positive constant. Linear homogeneity has a number of consequences for instance that $U=\sum_{i=1}^{m}\frac{\partial U}{\partial x_i}x_i$, where m is the number of extensive properties considered. The derivative $\partial U/\partial x_i$ is the *intensive property* connected to the extensive property x_i.

With an object made up of one substance and with intensive properties constant throughout the object, and $\mathbf{x}=[x_1,x_2,x_3]=[S,V,N]$, where S is entropy, V volume and N number of moles (mass), we have

$$U(S,V,N)=\frac{\partial U}{\partial S}S+\frac{\partial U}{\partial V}V+\frac{\partial U}{\partial N}N=TS-PV+\mu N, \tag{1}$$

where the derivatives (intensive properties) are interpreted as absolute temperature T, negative of absolute pressure P, and chemical potential μ.

Often the standard representation of internal energy in the literature does not use extensive variables alone as arguments. For instance for an object with temperature T and mass N, one would write $U=cNT$, where c is the specific heat capacity of the substance, N being extensive and T intensive. And the same formula would apply to an ideal gas, for which also the ideal gas law $PV=RNT$ applies, where R is the universal gas constant. For an object, not needing to consider volume, the internal energy function with only extensive arguments may be written

$$U(S,N)=const\;Ne^{S/(cN)}, \tag{2}$$

and for an ideal gas

$$U(S,V,N)=const\;e^{S/(cN)}V^{-R/c}N^{1+R/c}, \tag{3}$$

where *const* is an arbitrary positive constant (Grubbström, 1985, 2007, 2012).

Taking the relevant derivatives, it is easily found that $U=cNT$ is derived from either of Eqs. (2) and (3), and further that the ideal gas law $PV=RNT$ is a consequence of (3).

Assume there are two objects as energy sources and mechanical work W is to be extracted from the interaction of these objects through some device (a heat engine, a propeller, a turbine, etc.), (Fig. 1). The extensive properties of the objects are collected in the two vectors $\mathbf{x}^0$ and $\mathbf{x}^1$, and their internal energies are $U(\mathbf{x}^0)$ and $U(\mathbf{x}^1)$. Attempting to maximise W from this interaction gives the problem: Find $\hat{\mathbf{x}}^0$ and $\hat{\mathbf{x}}^1$ that maximise

$$W=\left(U(\mathbf{x}^0)+U(\mathbf{x}^1)\right)-\left(U(\hat{\mathbf{x}}^0)+U(\hat{\mathbf{x}}^1)\right), \tag{4}$$

subject to $\hat{\mathbf{x}}^0+\hat{\mathbf{x}}^1\geq\mathbf{x}^0+\mathbf{x}^1$, where equality holds except for the components representing entropy, and where the components of $\hat{\mathbf{x}}$ and $\hat{\mathbf{x}}$ are decision variables. This well-known optimisation problem leads to a solution in which each intensive property is equal for the two objects after extraction $\partial U(\hat{\mathbf{x}}^0)/\partial\hat{x}_i^0=\partial U(\hat{\mathbf{x}}^1)/\partial\hat{x}_i^1$. Thus tempera-

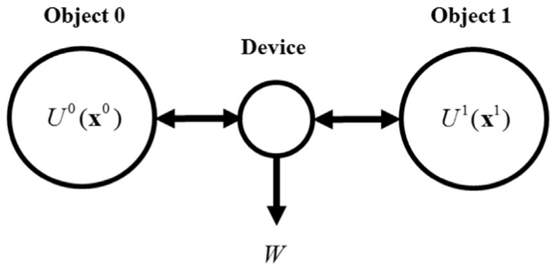

Fig. 1. Extraction of work W from pair of objects.

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