Thermodynamics and economics: Towards exergy-based indicators of sustainable development

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1. INTRODUCTION

The question of the relationship between thermodynamics and economic analysis is a difficult question, which has led to only sporadic research among both physicists and economists mainly during the last thirty years, i.e. since the beginning of the 1970's.

This transition field has lent itself, so to speak, to several levels of concern: a first level has been concerned with the role of thermodynamic constraints and principles on the constraints of production microeconomics. This concern has led to several works, which provide some interesting insights into the models of production microeconomics. From this particular angle, the early works of DE MONTBRIAL (1976), BERRY, SALAMON and HEAL (1978), LESOURD and GOUSTY (1981), LESOURD (1985), LESOURD and HALLEGATTE (1986) and LESOURD (1990) may be mentioned. These works deal with the relationships between the laws of thermodynamics and the concepts of production economics, such as production functions, and with the relationships between thermodynamic and economic optima.

A second concern has been linking the laws of thermodynamics and the constraints that they impose, with economic dynamics and, in particular, with the theory of long term growth. In this particular line of concern one can mention, some aspects of the work of DASGUPTA and HEAL (1979), the works of VAN GOOL and BRUGGINK (1985), MÅNSSON (1986), VAN DEN HEUVEL (1988), STERN (1997); related in some of their aspects are also the works of KRELLE (1984), PERRINGS (1986), and GERMAIN (1989), among others.

Finally, the works of GEORGESCU-ROEGEN (1971, 1979), as well as some more recent related works such as those of CLEVELAND and RUTH (1997), and FERRARI and LESOURD (2000) are interested in a third question: what are the implications of the irreversibility principle which results from the second law of thermodynamics?

This is only a *very partial survey* of the work that has been carried out in the cross-disciplinary field which lies between economics and thermodynamics.

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Few works, except perhaps for the aforementioned work of MÅNSSON (1986), which already dates back from 1986, have been devoted to the links between the above considerations and the sustainability of growth (or rather of development), from the angle of indicators of sustainable development. The second concern mentioned above is, however, related to this concept. This work intends to bridge a gap between thermodynamics and economics in this particular area. It is more precisely concerned with several objectives:

- Presenting a survey and the essential features of some of the work that has been carried out in our field;
- Reporting some possible directions of research in which one can consider exergy as a determinant of some suitable indicators for sustainable growth, providing examples and applications.

2. THERMODYNAMICS AND ECONOMICS: SOME FIRST ANALYSES

2.1 The laws of thermodynamics

The first law of thermodynamics, which implies energy conservation states that, in an isolated system, the total energy is conserved. This means that within the production process, that is, for a given system: „*the sum of energy inflows and outflows is zero*". It is merely a conservation principle, as there are many in other branches of physics.

But thermodynamics is the only branch of physics in which the economic concept of efficiency plays a central role, through the so-called *Carnot efficiency*. In particular, in the thermal production of physical work, or electricity, the second law of thermodynamics implies that the efficiency of heat, or its productivity from the economic standpoint, is upperly bounded by the Carnot efficiency:

$$\frac{W}{|Q|} \leq \eta < 1 \tag{1}$$

where Q stands for the heat used in the plant ($Q < 0$), because heat is a factor, and W stands for the physical work in the plant ($W > 0$, because physical work is a product). η stands for Carnot efficiency.

This stems from the second law of thermodynamics, which states that „*it is impossible to produce work with a machine operating cyclically with only one source of heat*" (Kelvin-Planck formulation of the second law of thermodynamics).

This formulation of the second law of thermodynamics may be deduced from a more general formulation saying that in any possible transformation in which a system evolves from state A to state B, with entropy variation $\Delta S = S_B - S_A$, there is some positive entropy creation:

$$\Delta S = S_B - S_A = \int_A^B \left[\frac{dq}{T} + d\hat{S}\right], \tag{2}$$

the entropy creation being nonnegative ($d\hat{S} \geq 0$), with $d\hat{S} = 0$ if, and only if, the transformation is reversible, while $d\hat{S} > 0$ if, and only if, the transformation is irreversible.

In particular, for a cyclical evolution ($B = A$):

$$\Delta S = \oint \left[\frac{dq}{T} + d\hat{S}\right] = 0 \tag{3}$$

So that:

$$\oint \frac{dq}{T} \leq 0 \tag{4}$$

In the case of a system related to a finite number of heat sources:

$$\sum_{i=0}^{n} \frac{Q_i}{T_i} \leq 0 \tag{5}$$

This is the so-called Clausius inequality if there are $n + 1$ sources of heat $0 \ldots i \ldots n$, with temperatures $T_0 < T_1 \ldots T_i < T_{i+1} \ldots T_{n-1} < T_n$.

Equation (3) of course implies that: „*In an isolated system, entropy increases over time (irreversible system) or remains constant (reversible system)*" (Clausius formulation of the second law of thermodynamics). This Clausius formulation may easily be shown to be equivalent to the Kelvin-Planck formulation.

2.2 *From the Clausius inequality to a price system*

As shown by several authors, such as BERRY, SALAMON and HEAL (1978), and GRUBBSTRÖM (1984), and as implied in an equivalent way in the Pareto-optimum model of LESOURD and GOUSTY (1981) these thermodynamic properties of heat imply a system of (using the terminology of GRUBBSTRÖM) *temperature-discounted prices.*

To establish this property, let us consider a cyclical thermal engine related to the above n+1 sources of heat, and using as resources $Q_0, Q_1 \ldots Q_i, Q_{i+1} \ldots Q_{n-1}, Q_n$ and the quantity of physical work W, with at least one strictly positive production other than Q_0. Let $\pi_0, \pi_1 \ldots \pi_i, \pi_{i+1} \ldots \pi_{n-1}, \pi_n$, and π_w be the respective (positive) prices of the various heats and of physical work. Our variables $Q_0, Q_1 \ldots Q_i, Q_{i+1} \ldots Q_{n-1}, Q_n$ and W are quantities of energy used, or produced, during a given finite time. They can therefore also be interpreted as quantities per unit time, or physical powers. This interpretation in terms of quantities per unit time will prevail henceforth for these variables, as well as for all other variables defined as energy, exergy, and entropy quantities (which are termed as *extensive variables* in the language of thermodynamics).

The profit Π of the firm operating the machine is:

$$\Pi = \sum_{i=0}^{n} \pi_i Q_i + \pi_w W \tag{6}$$

This profit may be maximized with respect to $Q_0, Q_1 \ldots Q_i, Q_{i+1} \ldots Q_{n-1}, Q_n$ and W, under the following constraints:

$$\sum_{i=0}^{n} \frac{Q_i}{T_i} - \hat{S} = 0 \tag{7}$$

and (first law of thermodynamics):

$$\sum_{i=0}^{n} Q_i + W = 0 \tag{8}$$

Eliminating Q_0 by using the last equation yields:

$$\sum_{i=1}^{n} Q_i \left(\frac{1}{T_i} - \frac{1}{T_0}\right) - \frac{w}{T_0} + \hat{S} = 0, \tag{9}$$

Multiplying by T_0, we obtain an equivalent form of the constraint:

$$\sum_{i=1}^{n} Q_i \left(1 - \frac{T_0}{T_i}\right) + W - T_0 \hat{S} = 0 \tag{10}$$

To maximize Π under constraint (10) with respect to $Q_1, Q_2 \ldots, Q_i, Q_{i+1} \ldots Q_{n-1}, Q_n$ and W, one must make specific hypotheses concerning the functional form of $\hat{S}$. As proposed by Berry, Salamon and Heal (1978), in particular, a simple hypothesis is to assume that, for a finite-time (hence irreversible) cycle, $\hat{S}$ is a semi-definite positive quadratic form, which stems from Prigogine's thermodynamics of irreversible phenomena:

$$\hat{S} = \frac{1}{2} \sum_{i,j=0}^{n} \beta_{ij} Q_i Q_j \tag{11}$$

The constraint being concave, the optimum is such that for any of the heat sources one has:

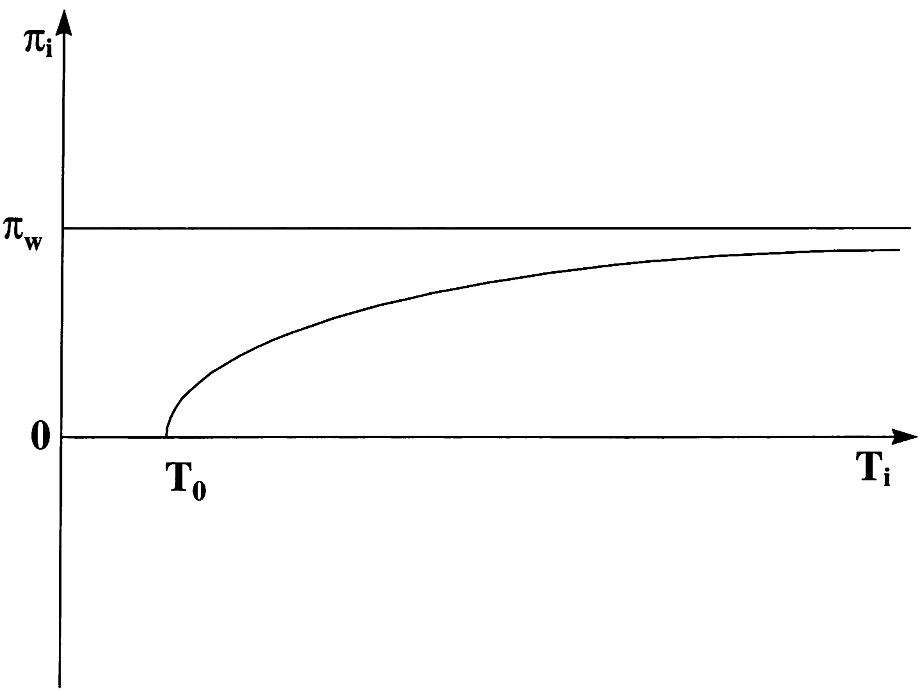
$$\frac{\pi_i}{\pi_w} = \left(1 - \frac{T_0}{T_i}\right) - \sum_{j=0}^{n} \beta_{ij} Q_j \tag{12}$$

Finally, whenever $Q_j \to 0$ for all j, i.e. close to reversibility, one has:

$$\frac{\pi_i}{\pi_w} = \left(1 - \frac{T_0}{T_i}\right) = \eta_i \tag{13}$$

where $\eta_i = (1 - T_0/T_i)$ is the Carnot efficiency associated to heat source i with reference to the coldest source 0.

Figure 1: GRUBBSTRÖM's temperature-discounted price



GRUBBSTRÖM's temperature-discounted price is closely related to an important concept, which is exergy. For any form of energy, in the particular case in which there is an available infinite cold source surrounding the system, the exergy content is defined as the product of the energy content by a quality factor $\eta_i = 1 - \frac{T_0}{T_i}$.

2.3 *Exergy and the production process*

The measure of the original quality of a resource refers to its ability to produce physical work. Because of the entropic property of the production process, any dissipation of energy or matter is a physical proof of wasting: both energy dissipation and matter dissipation increase entropy. Conversely, any entropy creation cannot be separated from exergy destruction, the maximum quantity of energy which can be extracted from a quantity of fuel. As MÅNSSON (1986) has pointed out, a limiting factor for the production process is the availability of exergy.

Let the following cardinal indicator be the exergy content of some heat Q at temperature T_1:

$$E = Q\left(1 - \frac{T_0}{T_1}\right) \tag{14}$$

Where Q is the heat quantity available from the fuel during the production process (the *enthalpy* of the fuel); T_0, the temperature of the cold source; T_1, the temperature of the hot source, at which the heat is made available. The exergy quantity E is *destroyed* in the production process.

When the production process effectively proceeds at a finite time, the qualitative change can be measured by the increase of heat dissipated into the environment, or transferred to the cold source. This is closely related to exergy destruction.

In order to define a rate of exergy destruction as an indicator for the production process sustainability, the substitution possibilities between inputs, output *product* and output *waste*, have to be taken into account.

More generally, let us consider the ability to produce physical work (per unit of time) in a production process, according to equation (10). Assuming first that the Q_i are inputs ($Q_i < 0$) leads to:

$$L = \Delta E = \sum_{i=0}^{n} |Q_i|\left(1 - \frac{T_0}{T_i}\right) - W = T_0\hat{S} \tag{15}$$

ΔE, which is the exergy loss or exergy destruction during the process, is clearly equal to the initial exergy present in the fuels, less the work effectively produced; it is closely related to the entropy creation in the process since:

$$L = \Delta E = T_0\hat{S} \tag{16}$$

3. SUSTAINABILITY, PRODUCTION PROCESSES AND IRREVERSIBILITY: EXERGY-BASED INDICATORS OF SUSTAINABLE DEVELOPMENT

3.1 Production processes and irreversibility

The second law of themodynamics, under the Clausius formulation, as shown above, may be called the entropy law. The economic implications of this law have been analyzed by GEORGESCU-ROEGEN (1971, 1976) and they lend themselves to stating the conditions of a sustainable production process.

According to this law, the production process changes a certain amount of energy and matter into heat, i.e. transforms irreversibly low entropy into high entropy. This has qualitative implications for the production process since it irrevocably produces waste output as a joint product. The famous implication of the second law is irreversible downgrading of energy.[1]

Following the second law of thermodynamics, sustainability of a production process depends upon the quality of all the elements (including the inputs) which flow through it during period of time. The production process, by transforming natural resources into products and wastes, belongs to an ordinal reading. The qualitative variation of the process measured by the entropy variable can be related to a low-quality residual: waste.

Waste production may be seen as an implication of the irreversibility of production processes. Dissipation takes place any time waste is produced.

In this context, only part of the waste can be re-used without entropy creation, or exergy destruction: it is so to speak dissipated matter, under a form which is not useful from the economic point of view.

It is possible to measure sustainability of a production process by taking into account its degree of irreversibility, which is related to its ability to produce waste in general, and dissipated energy in particular. This point will be developed later.

3.2 Substituability property and sustainability

Sustainability is usually related to the characteristics of natural resources that are used in the production process. The degree of substitution between the inputs defines a weak or a strong sustainability of the development (PEARCE and TURNER, 1990). The sustainability of the development is endangered when no substitution possibility exists (STERN, 1997).

Owing to the thermodynamic analysis of the production process, the substituability property has a twofold dimension, as it is related to both the nature of inputs and their arrangement within the production process.

1. GEORGESCU-ROEGEN has transposed the entropy law to matter. In this context, he formulated a so-called „fourth law of thermodynamics" whereby, in a closed system, matter is irrevocably dissipated.

Substitution is carried out *ex ante*, before implementing the production process. Thus, it is only concerned with the marginal product of inputs, irrespective of wastes.

This first form of substitution has a cardinal dimension. Only the conservation laws of physics, including the first law of thermodynamics, apply: in particular, within the production process, inflows and outflows have the same mass according to mass conservation.

In the context of the second law of thermodynamics, substitution allows us to take into account input quality. It thus acquires an ordinal dimension, and leads to some heterogeneous arrangement of production factors. Here, we do not substitute one tonne of coal by one tonne of oil products, but some quality of a particular fuel by some quality of another one.

The implementation of a sustainable production process may take either of the following two directions:

- substitutions among different high energy potential inputs, especially when renewable energy inputs substitute for non-renewable inputs;
- indirect substitution through improved efficiency in the combination of inputs: this is related to possible substitutions between energy and other non-energy inputs, such as capital and labour, leading to higher efficiencies.

Taking into account the exergy dimension of a production process with indirect substitutions allows us to define a condition for sustainability, since only substitutions that reduce entropy creation, or exergy destruction, must be pursued.

3.3 Sustainable technologies: irreversibility and exergy destruction

Georgescu-Roegen's definition of a feasible technology, in his analysis of a production process through a flow-fund approach, emphasizes the role of technology within the duration of the process. Technology defines the accessibility of any input present in the production process. Carnot efficiency defines the upper limit for the efficiency of the transformation. Furthermore, energy flows are always necessary as energy inputs are essential. However, actual technologies saving non-renewable energies are feasible technologies, but they are not sustainable technologies since they still rest on fossil fuels. Thus, any indicator of fossil energy conservation must take into account two things: actual energy savings concerning fossil fuels, which is related to the exergy efficiency of processes, and substitution of renewable energies to fossil fuels.

For any energy input, and especially in the case of fossil fuels, a measure of the following two items must be considered:

- the original quality, at a given time t, of the available quantity of energy (cardinal indicator)
- the change of the original quality of the available quantity of energy for a given duration of time (ordinal indicator)

The measure of the original quality of a resource refers to its ability to produce physical work. Clearly, any exergy destruction is equivalent to entropy production. Conversely, any entropy creation is equivalent to exergy destruction, exergy being the largest possible quantity of high-grade energy (mechanical work, electricity) which can be extracted from a given quantity of fuel. As pointed out by MÅNSSON (1986), a limiting factor for any production process is the availability of exergy, not the availability of energy regardless of its quality.

For any form of energy, as shown above, the exergy content is defined as the product of the energy content by a quality factor f, with $0 \leq f \leq 1$.

We are thus led to defining a most general rate of exergy destruction λ, with $\lambda \in [0, 1]$:

$$\lambda = \frac{\sum_m J_m + \sum_n W_n}{\sum_j I_j + \sum_k E_k} \tag{17}$$

with the following definitions: J_m is the exergy available per unit time in waste of kind m produced; W_n is the exergy available per unit time in the energy output n; I_j is the exergy input per unit time in material nonfuel factor j; E_k is the exergy input per unit time in the fuel or energy factor k. Especially in the case of non-renewable inputs such as fossil fuels, the higher λ, the more the production process is sustainable in that it saves more non-renewable resources and produces less recyclable wastes, their recyclability being measured by their exergy. When the exergy yield increases, the rate of exergy destruction decreases, i.e. the waste production is reduced. For a given energy flow and for unchanged input quantities, the amout of exergy destroyed depends only upon the arrangement of inputs. Sustainability stems from the qualitative dimension of the production process, and more precisely from its exergy efficiency.

In the particular case of energy production, in which only energy inputs and energy outputs are obtained, we have:

$$\lambda = \frac{\sum_n W_n}{\sum_k E_k} \tag{18}$$

Here, λ is equivalent to the so-called second-law efficiency Ψ of the process, defined as:

$$\Psi = \frac{\sum_n Q_n\left(1 - \frac{T_n}{T_0}\right) + \sum_{n'} W_{n'}}{\sum_k Q_k\left(1 - \frac{T_k}{T_0}\right) + \sum_{k'} W_{k'}} \tag{19}$$

Although (18) is physically meaningful regardless of the renewable character of the energy inputs, it is a meaningful indicator of the sustainability of the process only if the energy sources are non-renewable. It indicates, in that case, the more or less efficient way in which these non-renewable energy inputs are being used.

In the case of a number N of independent and additive energy-using processes $1 \ldots u \ldots N$ such as, for instance, a macroeconomic entity, let λ_u be the pertinent value of λ, as defined by (18), for process u. We can thus calculate an exergy input-weighted index Λ as:

$$\Lambda = \frac{\sum_u \lambda_u E_u}{\sum_u E_u} \tag{20}$$

In this equation, E_u stands for the exergy input for process u per unit time. However, this index is meaningful only for non-renewable energies. If renewable energies are being used, then one must take into account the fact that, in this case, the exergy loss may be recovered from the renewable energy source as if the process were reversible. We are thus led to the following general index:

$$\Phi = \frac{\sum_u \phi_u E_u}{\sum_u E_u} = \sum_u \phi_u \omega_u \tag{21}$$

with $\phi_u = \lambda_u$ for a non-renewable energy source, and $\phi_u = 1$ for a renewable energy source, or for the limiting case of a reversible process.

Finally, the sustainable development indicator that we propose here aims at capturing the importance of non-renewable energy savings in the production of secondary energies such as electricity. As mentioned above, these are related, firstly, to the exergy efficiency of processes using fossil fuels, and, secondly, to substitution of renewable energy inputs to these fossil fuels.

4. EMPIRICAL APPLICATION

4.1 The case study

Our empirical application deals with a specific energy service, namely: the production of heat for heating residential areas. Our purpose is, firstly, to assess the potential primary energy savings implied by substituting the traditional swiss heating system, based on the combustion of fossil fuels in a boiler, with less conventional heating systems like the electric heater, the electric-pump or the combined heat-power (CHP) system matched with an heat-pump. Secondly, we compute and compare the value of the sustainable development indicator (21) for all these heating systems.

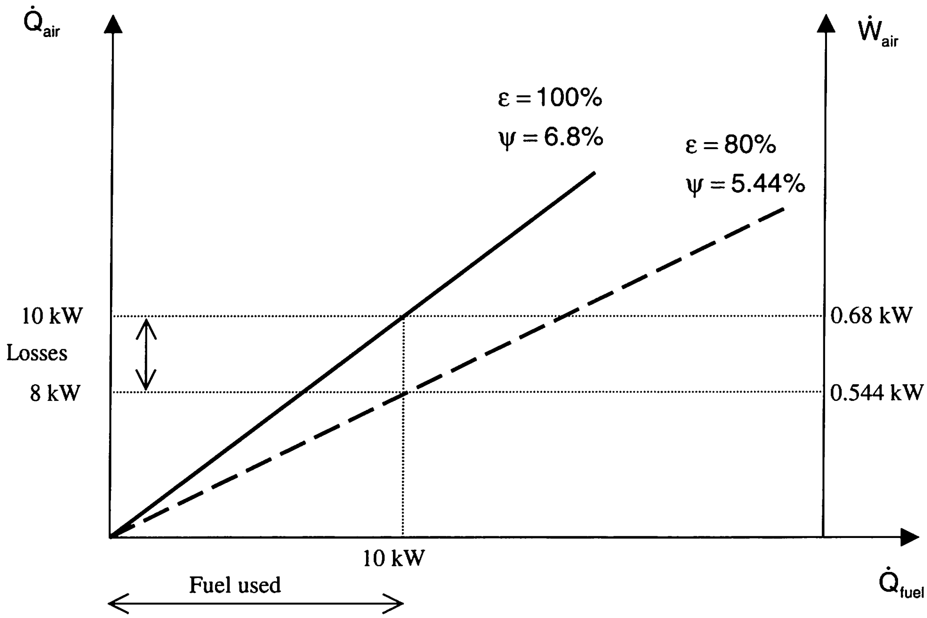
4.2 Computing the exergy efficiency of heating systems

To value the energy transferred to the atmosphere of an heated room, we estimate the energy losses of a boiler, according to the first principle of thermodynamics, to a rate of

20 %, including the heat losses of the network of hot water distribution. The primary energy consumption of an heating system is therefore the sum of the thermal energy required for heating and of the energy losses according to the first principle of thermodynamics.

In figure 2, we display the reference heating system, namely a boiler fueled with oil.[2]

Figure 2: The reference case of a boiler fueled with oil



With a boiler of energy heating power $\dot{Q}_{\text{fuel}}$= 10 kW, the energy power transferred to the heated air is $\dot{Q}_{\text{air}}$ = 8 kW, if the energy efficiency of the heating system is ε = 80 %.[3] With reference to a temperature of the heated room of T_{air} = 20°C = 293.16 °K and to an outside temperature of T_0 = 0°C = 273.16 °K, the exergy power of the heated air is therefore equal to:

$$\dot{W}_{\text{air}} = Q_{\text{fuel}}\left(1 - \frac{T_0}{T_{\text{air}}}\right)\varepsilon = 10 \cdot \left(1 - \frac{273.16}{293.16}\right) \cdot 0.8 = 0.544 \text{ kW}. \qquad (22)$$

2. To avoid confusion, we use, in what follows, only instantaneous rates of energy consumption called powers. These rates will be denoted, as conventional, by the dot-symbol of time derivative.
3. We assume that the heat produced by the boiler is distributed via a hot-water network with working temperatures of 80°C/60°C equipped with radiators.

This way to compute $\dot{W}_{\text{air}}$ applies whatever heating system being used. For instance, if no energy losses occur, namely for $\varepsilon = 100\,\%$, the exergy power of the heated air is:

$$\dot{W}_{\text{air}} = \dot{Q}_{\text{fuel}}\left(1 - \frac{T_0}{T_{\text{air}}}\right)\varepsilon = 10 \cdot \left(1 - \frac{273.16}{293.16}\right) \cdot 1 = 0.68 \text{ kW}. \tag{23}$$

At the contrary, the exergy power content of the fuel depends on the heat production system.

When a boiler is used, the exergy power of the burned fuel is, by definition:

$$\dot{E}_{\text{fuel}} = \dot{Q}_{\text{fuel}} = 10 \text{ kW}. \tag{24}$$

Therefore, the exergy efficiency (19) of this heating system is:

$$\Psi = \left(1 - \frac{T_0}{T_{\text{air}}}\right)\varepsilon = 5.44\% \tag{25}$$

For an electric heater the exergy power content of the fuel depends on the type of power station that produces the electricity used. Hence, we compute it according to:

$$\dot{E}_{\text{fuel}} = \dot{Q}_{\text{fuel}}\lambda_{\text{power station}} = 10 \text{ KW } \lambda_{\text{power station}} \tag{26}$$

where $\lambda_{\text{power station}}$ denotes the exergy efficiency of the power station, set to 50 % for a thermal power station, 32 % for a nuclear power station and 93 % for an hydropower station.[4] Therefore, for an electric heater, formula (19) leads to an exergy efficiency of:

$$\Psi = \frac{\left(1 - \frac{T_0}{T_{\text{air}}}\right)\varepsilon}{\lambda_{\text{power station}}} \tag{27}$$

The efficiency figures for the three above mentioned power stations are presented below in table 1 (heating systems 2, 3 and 4).

To compute the exergy efficiency of an heat-pump, we shall also take into account the exergy power of the compressor. The exergy power delivered to the heated room by the condenser must be identical to that transferred by the previous heating systems. The difference between the exergy power of the compressor and that of the condenser is the exergy power of the evaporator, a device that transfers the energy of the air towards the compressor.

Assuming a practical coefficient of performance of the heat-pump equal to 50 % of its theoretical value, namely:

4. See REISTAD (1975).

$$\mathrm{COP}_{\text{theoretical}} = \frac{T_{\text{condenser}}}{T_{\text{condenser}} - T_{\text{evaporator}}} = 4.26 \tag{28}$$

and average operating temperatures of the condenser and of the evaporator of $T_{\text{condenser}} = 80°\text{C}$ and $T_{\text{evaporator}} = -3°\text{C}$ respectively,[5] the exergy power content of the fuel is:

$$\dot{E}_{\text{fuel}} = \frac{\dot{Q}_{\text{condenser}}}{0.5\ \mathrm{COP}_{\text{theoretical}}} \lambda_{\text{power station}} = \frac{10\ \text{kW}}{0.5 \cdot 4.26} \lambda_{\text{power station}} = 4.7\ \text{kW}\ \lambda_{\text{power station}} \tag{29}$$

Finally, the exergy efficiency of the heat-pump turns out to be:

$$\Psi = \frac{\dot{Q}_{\text{fuel}}\left(1 - \frac{T_0}{T_{\text{air}}}\right)\varepsilon}{\frac{\dot{Q}_{\text{condenser}}}{0.5\ \mathrm{COP}_{\text{theoretical}}} \lambda_{\text{power station}}} \tag{30}$$

As far as a CHP system matched with an heat-pump is concerned, the exergy power of the fuel is the sum of the exergy power of the condenser and of the recuperator, namely:

$$\dot{E}_{\text{fuel}} = \dot{E}_{\text{condenser}} + \dot{E}_{\text{recuperator}} = \frac{\dot{Q}_{\text{fuel}}}{0.5\ \mathrm{COP}_{\text{theoretical}} \cdot \varepsilon_{\text{electric}} + \varepsilon_{\text{thermal}}} = 8.3\ \text{kW} \tag{31}$$

where $\varepsilon_{\text{electric}} = 27\,\%$ and $\varepsilon_{\text{thermal}} = 63\,\%$ denotes the energy efficiencies of CHP electricity production and of heat recuperation respectively. Hence, the exergy efficiency of this heating system is:

$$\Psi = \left(1 - \frac{T_0}{T_{\text{air}}}\right)\varepsilon\ (0.5\ \mathrm{COP}_{\text{theoretical}}\varepsilon_{\text{electric}} + \varepsilon_{\text{thermal}}) \tag{32}$$

4.3 Results and discussion

By combining the four heating systems previously analysed with four different technologies of electricity production, namely:

- thermoelectricity
- hydroelectricity
- nuclear electricity
- swiss-mix electricity (2.34 % of thermoelectricity, 40.05 % of nuclear electricity, 57.61 % of hydroelectricity)

5. These are normal working temperatures for a heat-pump connected to a hydro-network of heat distribution.

we define ten heating systems whose performances are compared in table 1. These heating systems are:

1. boiler fueled with oil or natural gas
2. electric heater fueled with thermoelectricity
3. electric heater fueled with hydroelectricity
4. electric heater fueled with nuclear electricity
5. electric heater fueled with swiss-mix electricity
6. heat-pump fueled with thermoelectricity
7. heat-pump fueled with hydroelectricity electricity
8. heat-pump fueled with nuclear electricity
9. heat-pump fueled with swiss-mix electricity
10. CHP system fueled with natural gas or oil matched with an heat-pump.

Table 1: Heating system's performances

Case	Ψ	Q	Net energy saving		Φ
	%	TJ/year	%	TJ/year	%
1	5.44	235.90	–	–	5.44
2	2.72	471.80	−100.0	−235.90	2.72
3	5.04	254.62	−7.9	−18.72	100.00
4	1.76	729.15	−209.1	−493.25	1.76
5	3.67	349.46	−48.1	−113.56	58.38
6	5.68	225.39	4.2	9.97	5.68
7	10.24	125.32	46.9	110.58	100.00
8	3.60	356.47	−51.1	−120.57	3.60
9	7.47	171.70	27.2	64.20	59.19
10	6.56	195.62	17.1	40.28	6.56

The first column of table 1 compares the exergy efficiency of the ten heating systems. The best efficiency is achieved by a heat-pump fueled with hydroelectricity ($\psi = 10.24\,\%$) while the worst is that of a heat-pump fueled with nuclear electricity ($\psi = 1.76\,\%$).

Using the actual annual fuel consumption of the residential buildings rented by the City of Geneva, namely 235.9 TJ/year,[6] we estimated the fuel consumption necessary to provide the same heating service if we switch from the actual heating system, namely a boiler fueled with oil or natural gas, to one of the nine other heating systems we consider. These figures, as well as the net energy savings implied by this heating system's changes, are presented in columns two to four of table 1. We can see that the most exergy efficient heating system, namely the heat-pump fueled with hydroelectricity, allows a fuel saving of 46.9 % corresponding to an energy conservation of 110.58 TJ/year. The

6. These figure has been provided by the Energy Service of the City of Geneva.

second best heating system, an heat-pump fueled with swiss-mix electricity, still allows an energy saving of 27.2 % corresponding to 64.20 TJ/year.

The last column of table 1 present the value of the sustainable development indicator (21) computed for each of the ten heating systems. As an illustration, we show how to calculate this indicator for an heat-pump fueled with swiss-mix electricity, namely:

$$\Phi = 1 \cdot \omega_{\text{hydro}} + \lambda_{\text{thermal}} \cdot \omega_{\text{thermo}} + \lambda_{\text{nuclear}} \cdot \omega_{\text{nuclear}} \tag{33}$$

where λ_{thermal} and λ_{nuclear} stands for the exergy efficiency of thermoelectricity and nuclear electricity respectively and $\omega_{\text{hydro}}, \omega_{\text{thermo}}, \omega_{\text{nuclear}}$ denote the shares of hydroelectricity, thermoelectricity and nuclear electricity in the swiss-mix electricity.

Clearly, this indicator achieves its maximum value of 100 % only for a heating system exclusively fueled with renewable energy, like the electric heater or the heat-pump fueled with hydroelectricity. When only non renewable fuel is used the sustainable development indicator is identical to the exergy efficiency presented in the first column of table 1. Therefore, this indicator provides a new information only for the two heating systems fueled with swiss-mix electricity, partly produced with renewable and partly with non renewable energies. In these cases we observe very close figures due to the high share of hydroelectricity in the swiss-mix and to the very low exergy efficiency of the heating systems fueled with nuclear electricity, still substantial in the swiss-mix.

5. CONCLUSION

In this paper, we discuss an exergy-based indicator of sustainable development. This indicator takes into account the two ways in which energy savings savings can be achieved. Firstly, it takes into account the average exergy efficiency, or second law efficiency, concerning fossil fuels; secondly, it takes into account the importance of renewable energy sources being used as substitutes for fossil fuels. This indicator can be expressed as 1 – (rate of exergy destruction) obtained from non-renewable energy sources, as shown by equation (21). At the microeconomic level, it is equal to the second-law efficiency of the process for a non-renewable primary energy source, and to 1 otherwise. It is equal to 1 for either a renewable energy source, or for a (limiting) reversible process, and equal to zero for energy coming from a non-renewable energy source which is entirely dissipated, or transferred to the cold source. For a microeconomic entity such as a cross-section, or for a macroeconomic quantity, it is equal to the power-weighted average of the above microeconomic indicators.

A simple empirical application shows us how to practically implement the computation of such an indicator in the case of heating facilities existing in the city of Geneva under several hypotheses concerning the heating technologies being used. With the current swiss electricity production mix, the sustainable development index of space heating is about 60 %, a rather high figure due to the importance of hydropower plants, considered as renewable primary energy sources, in the case of Switzerland.

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SUMMARY

The main purpose of this paper is to define indicators of sustainable development which take into account the economic constraints imposed by the laws of thermodynamics. Firstly, a survey of some essential work about the relationships between economics and thermodynamics is proposed. Secondly, the exergy concept is introduced as a tool which describes irreversibility in production processes. Finally, an indicator of sustainable development which aims at taking into account energy savings at the level of some macroeconomic aggregate, is provided. This indicator is, among other things, based on is exergy efficicency. It is also applied to heat production, on the basis of a case study.

ZUSAMMENFASSUNG

Hauptziel dieses Artikels ist, Indikatoren der nachhaltigen Entwicklung zu definieren, welche die ökonomischen Restriktionen berücksichtigen, die mit den thermodynamischen Gesetzen verbunden sind. Zu Beginn werden einige wichtige Arbeiten über die Beziehungen zwischen Ökonomie und Thermodynamik vorgestellt. Anschliessend wird das Konzept der Exergie eingeführt zur Beschreibung der Irreversibilität im Produktionsprozess. Danach wird ein Indikator der nachhaltigen Entwicklung konstruiert, der die Energieeinsparungen in einem makroökonomischen Aggregat beschreibt, wobei er sich insbesondere auf den exergetischen Wirkungsgrad abstützt. Schliesslich wird dieser Indikator an der Wärmeproduktion anhand einer Fallstudie angewandt.

RESUME

L’objet majeur de notre article est de définir des indicateurs de développement durable qui prennent en compte les contraintes économique liées aux principes de la thermodynamique. Tout d’abord, une étude de quelques travaux majeurs sur les relations entre l’économie et la thermodynamique est proposée. Le concept d’exergie est ensuite intro-

duit comme l'irreversibilite du processus de production. Puis, un indicateur de developpement durable décrivant les économies d'énergie au sein d'un agrégat macroéconomique est construit, en s'appuyant notamment sur la notion de rendement exergétiques. Cet indicateur est appliqué à la production de chaleur sur la base d'une étude de cas.