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The Wasted Primary Resource Value: an Indicator for the Thermodynamics of Sustainability for Municipalities Policy

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Abstract

Exergy is a thermodynamic quantity which allows us to obtain information on the useful work obtainable in a process. The analyses of irreversibility are important in the design and development of the productive processes for the economic growth, but it plays a fundamental role in the thermodynamics analysis of socio-economic context of municipality. Consequently, the link between the wasted exergy and the energy cost for maintain the productive processes are linked based on the bioengineering thermodynamics. This link holds to the fundamental role of fluxes and to the exergy exchanged in the interaction between the system and its environment. A new indicator, the equivalent wasted primary resource value for the work-hour, is suggested to support the public managers for their economic decisions. Here, the Alessandria Municipality is analyzed in order to highlight the application of the theoretical results.

Keywords: *Bioeconomy; entropy; exergy; inefficiency; irreversibility; sustainability; thermoeconomy*.

1. Introduction

Nowadays, growth is considered an imperative. In the analysis of the relation between energy and economic development it has been pointed out how development affects energy use, but it doesn't happen that the energy use affects development [1]. But, it is clear that energy plays a fundamental role in promoting the economic growth [2-5], because energy is an essential factor of production because all economic processes require energy, while the economic analyses of growth are usually focused on the capital and labour.

In the economics of production a key concept is represented by reproducibility (for example this concept is related to capital, labour, etc.), even if some inputs, like energy and information, are non-reproducible [3, 6]: but, many researchers have emphasized the role of energy and its availability in the economic production and the related growth [7,8].

In this context, it is possible to introduce a question: is the economic growth the real aim of the present developed society? Or a developed society is no more than a stationary socio-economic state with a diffused richness? The answer to these question will represent the last discussion of this paper. Now, we introduce the preliminary considerations on which we will focus our analysis.

Moreover, one of the main problems of industrialized countries is the management of CO_2 emissions. On April 23rd 2009, The European Parliament and the Council adopted the Directive 2009/28/EC on the promotion of the use of energy from renewable sources: it represents the European Union common basis for the promotion of renewable energy [9]. Moreover, economic strategy for the sustainable development suggest both to improve energy efficiency and to introduce a rational use of energy in all the member states of the European Union [10].

In 1988, it has been highlighted both how the improvements towards greater and greater energy efficiency are limited by the laws of thermodynamics [11], and that the aim of any design, policy and analysis should be the optimum balance among economic, social, environmental, political acceptability factors, security included [11,12]. Moreover, it has been evaluated that the potential thermodynamic improvements result of around 80%, but only the 50% of the energy can be saved by technical means, while the economic barriers reduce it at the 30% [12,13].

Many factors can affect overall carbon dioxide emissions: economic growth levels, technological development, and production process selected for any particular production [14]. At the same time, the CO_2 emission problem could represent a real opportunity to promote high-efficiency design of conventional plants, and consequent dissemination of advanced technologies. Indeed, the European Union also designed the Strategic Energy Technology (SET) Plan, to develop researches on new technologies, with particular regard to those relevant in climate change [15]: measurement, tracking, and program evaluation are important to evaluate the impact of the sustainable policy, with particular regard to emissions reductions.

But, thermo-economy is a very effective thermal engineering approach to study the industrial processes, while it isn't so effective in the analysis of the processes which involve also social aspects. Now, the question is: at present, may an approach not consider also the social aspect of the economic system? Looking around, obviously the answer is: no. The great number of problems, inside and outside the specific society, cannot forget any social consideration. But, this requires a change of standpoint. Indeed, it has been pointed out that the appropriate

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technologies start from the consideration that there are many ways to find solutions to a problem, that any solution presents also cultural consequences [13,16,17].

So, we wish to define a new approach, based on the biological systems, but analysed by the thermal engineering approach, the bio-thermo-economics. To do so, first we must introduce some considerations on biological systems in relation to the economic, industrial and social perspectives, then we can summarize the bases of the thermodynamic approach to such systems, and, last, we will reconsider the sustainability as the results of continuous interactions of subsystems of a more complex system, which is the socio-economic one.

2. Preliminary Considerations

In the entire scientific history, scientists and engineers tried to obtain universal principles useful to the evaluation of the system's developments: examples being Fermat's principle in optics and Hamilton's principle in mechanics, Prigogine's least entropy production [18-22], in thermodynamics, in order to describe the dissipative systems, used in a several energy efficiency problems in design and optimization of thermal and power systems [23-25]. The entropy approach was first introduced in industrial ecology by Lowenthal and Kastenberg [26], whose results were to assign an entropy value, interpreted as a cost, to stages in a product's life cycle, but its use was also a thermodynamic measure for resource use, or waste generation [27].

In order to determine how far a process, or a system, is from its maximum thermodynamic performance, exergy can be introduced [28-30]; indeed, exergy losses and thermodynamic efficiency are related to assess thermo-economic costs [31]. It has also be shown that by exergy balance analysis it is possible to define a new quantity, the exergy inefficiency, named also unavailability percentage, which used together the economic indicator, a quantity which gives the equivalent primary resource value for the work-hour, can be consider an interesting indicator for accounting both the economic energy cost and the thermodynamic loses in any process [32,33]. But, in this section we wish to highlight the bases of the suggested approach.

The first hypothesis is that an economic system is a complex one, and, in particular it can be accounted as a biosystem, i.e. an adaptive and self-organized open system [34]. In the last five years, for such systems a bio-engineering thermodynamic approach was developed in order to evaluate irreversibility and dissipations, globally evaluated by the evaluation of the entropy generation [35-38]. The thermodynamic approach to such systems is based on the consideration that any effect in Nature is always the consequence of the dynamic balances of the interactions between the real systems and their environments [35-46]. Energy balances are the results of the exchange of exergy [30], between any real system and its environment [35-46]. The real systems evolution is always related to the decrease of their free energy, in the least time [28-30,44-46].

So, we consider the environment as a thermostat, and the system, together with its environment, is an adiabatic closed system [35]. But, for an adiabatic close system, the total entropy can be evaluated as [47]:

$$dS = d_iS + d_eS \tag{1}$$

where dS is the variation of the total entropy elementary, d_eS is the entropy variation for interaction between the open system considered and its environment, and d_iS is the entropy variation due to irreversibility. So, the total entropy always increases, as a consequence of the second law [28-30,44-46]:

$$\frac{dS}{dt} \geq 0 \tag{2}$$

Now, we can write Eq. (1) as [47]:

$$\frac{dS}{dt} = \int_V \left[-\nabla \cdot \left(\frac{Q}{T}\right) + \dot{s_g}\right] dV \tag{3}$$

where Q is the heat flow, T is the temperature, V is the volume, t is the time and $\dot{s}_g$ is the density of the entropy generation rate. Now, we consider that the stationary states of the open system correspond to the equilibrium states of the adiabatic closed system. Considering the system together with its environment, we are analysing an adiabatic closed system, so the entropy variation for the volume considered is maximum at the equilibrium [47]:

$$dS = 0 \Rightarrow -\nabla \cdot \left(\frac{Q}{T}\right) + \dot{s_g} = 0 \tag{4}$$

and

$$\nabla \left(\frac{Q}{T}\right) = \dot{s_g} \tag{5}$$

This last relation allows us to state that the flows between the open system and its environment cause the entropy generation rate density, so the interaction between system and environment is responsible of irreversibility: without interaction no irreversibility occurs. Now, considering that the entropy generation rate density can be written as [47]:

$$\dot{s_g} = \sum_k J_k X_k \tag{6}$$

where $\mathbf{J}_k$ is the flow of the k-th quantity involved in the process considered and $\mathbf{X}_k$ is the related thermodynamic force. In relation to the mathematical form (6) we must highlight the Curie principle [48] for which fluxes and forces of different tensor properties are never coupled, so that we can consider the different component to be always independent one another [47]. Now, considering that:

$$\nabla \left(\frac{Q}{T}\right) = Q\nabla \left(\frac{1}{T}\right) + \frac{1}{T}\nabla Q = \sum_k J_k X_k \tag{7}$$

Eq. (5) becomes:

$$\frac{1}{T}\nabla Q = \sum_k J_k X_k - Q\nabla \left(\frac{1}{T}\right) \tag{8}$$

In agreement with Le Chatelier's principle [49], for which any change in concentration, temperature, volume, or pressure generates a readjustment of the system in opposition to the effects of the applied changes in order to establish a new equilibrium, or stationary state.

It follows that the fundamental imperative of Nature is to consume free energy in least time. This quest will yield the ubiquitous scale-free patterns [49]. Any readjustment of the state of the system can be obtained only by generating fluxes of free energy which entail any process where the system evolves from one state to another.

The approach previously summarized allows us to introduce some considerations [35]:

1. The energy lost by a system is gained by the environment, consequently, the information lost by the system is gained by the environment: here the problem is to codify this information;
2. The environment is completely accessible by any observer, so it is easy to collect data on the lost energy of any system;
3. The flows cause entropy generation variations, consequently we can evaluate the entropy generation to obtain information to the flows, even when we are unable to evaluate the flows themselves;
4. The entropy generation is a global quantity, so we can obtain global information on the cells, but from a biomedical point of view just the global cells behavior is the useful information.

By taking into account these last physical considerations we can state the following considerations:

1. An open irreversible real linear or non-linear system is considered;
2. Each process has a finite lifetime τ;
3. What happens in each instant in the range $[0,\tau]$ is unknown, but what has happened after the time τ is always known;
4. The local equilibrium is required to define the global thermodynamic quantities;
5. The balance equation is a balance of exergy fluxes.

The fundamental hypotheses of this approach are:

1. The work lost for irreversibility is energy collected by the environment;
2. The environment temperature, always considered constant during any process.

This approach is interesting in science, engineering, and economics because it allows us to analyse complex systems, partially inaccessible, on which our knowledge is, consequently, only partial. Adaptive systems represent example of such systems because they are able to adapt to the variation of environmental conditions by attaining their “optimal” performance by a selection process driven by their environment. The resultant effect is a redistribution of energy and mass flows in their energetic network, by using regulatory subunits. It is no more than the engineering thermodynamic analysis of the steady-state flux distribution, which are no more than the exergetic, or "metabolic", flows.

3. The Exergy Inefficiency

As a consequence of the previous results, any change in the energy of an open system can be expressed in terms of the transfer of flows of matter across the system boundary, which bring internal, kinetic, chemical, heat, and other form of energy across the system boundary, and performance of work developed by or on the system. Any process, interaction, cycle, etc. occur in a specific time τ, which can be considered the lifetime of this phenomenon. Consequently, the energy used by a system, E, results:

$$E = \sum_i \int_0^\tau \dot{m}_i \big(h + e_k + e_p + e_{ch}\big)_i \, dt + \sum_j Q_j - W \qquad (9)$$

where h is the specific enthalpy, e_k is the specific kinetic energy, e_p is the specific potential energy, e_{ch} is the specific chemical energy, $\dot{m}$ is the mass flow, Q is the heat exchanged and W is the work developed, the suffixes i and j are related to the matter flows across the boundary of the system, using the positive sign for the incoming flows and the negative sign for the out coming ones. As a consequence of this energy variation, the following entropy variation, ΔS, of the system occurs:

$$\Delta S = \sum_i \int_0^\tau \dot{m}_i s_i \, dt + \sum_j \frac{Q_j}{T_j} + S_g \qquad (10)$$

where T is the temperature, s is the specific entropy and S_g is the entropy variation due to irreversibility, the entropy generation. This last term represents the degradation of energy, i.e. the energy dissipated during any process for friction, viscosity or any other cause of irreversibility. It can be evaluated in the environment. The flow of the wasted exergy allows us to obtain information on the ability of the system to be optimized.

Now, it is possible to combine the two equations and obtaining the equation of balance for exergy, known as efficiency equations for the real case:

$$W_t = \sum_i J_{ex,i} + \sum_j Ex_{Q,j} - T_0 S_g - \Delta B \qquad (11)$$

where W_t is the useful work (technical work), $J_{ex} = \int_0^\tau \dot{m}(e - T_0 s)dt$ is the flow exergy due to mass flow, $Ex_Q = (1 - T_0/T)Q$ is the exergy transfer due to heat transfer, $B = (E + p_0 V - T_0 S)$ is the accumulation of non-flow exergy, and $Ex_{ch} = \sum_l n_l(\mu_l - \mu_{l0})$ is the chemical exergy, with n molar number and μ chemical potential. Now, if there are no irreversibility then $S_g = 0$ J K^{-1} and the useful work is the maximum work $W_{t,max}$ that could be done. Consequently, it follows that:

$$S_g = \frac{W_\lambda}{T_0} = \frac{1}{T_0}(Ex_{in} - Ex_{out} - W) \qquad (12)$$

where W_λ is the work lost for friction, viscosity and any other irreversibility and the entropy generation is the entropy variation caused by these irreversible processes, while *in* and *out* means inflow and outflow respectively. A deep discussion of the exergy can be found in Ref. [32].

As a consequence of the previous considerations, in bioengineering thermodynamics and thermoeconomics, the concept of exergy results useful to evaluate the available energy for conversion from a reservoir with a reference to the ambient environmental temperature, representing the thermodynamic quality of the energy of a system.

Now, considering the relation (12) we can define a parameter useful to quantify the technological level of a process related just to the unavailability, named exergy inefficiency, as:

$$\varepsilon_\lambda = \frac{T_0 S_g}{Ex_{in}} \qquad (13)$$

We have shown that propose this quantity as useful to evaluate the technological maturity of a production system or a production sector in a country, because it allows us to obtain information on the losses of processes. The less is the value of the unavailability percentage the more the industrial process is efficient in terms of energy use [32,33].

Here we want to use it also to define the sustainability of a process. To do so we consider also the equivalent primary resource value for the work-hour *EI*, defined as:

$$EI = \frac{Ex_{in}}{n_h n_w} \tag{14}$$

where n_h is the number of work hour, and n_w the number of workers. This quantity indicates the exergetic cost necessary to support the workhours and to generate capital flows. Now, combining this two indicators, we can obtained a new indicator, the equivalent wasted primary resource value for the work-hour:

$$EI_\lambda = \varepsilon_\lambda EI = \frac{T_0 S_g}{n_h n_w} \tag{15}$$

This quantity is interesting because it allows us to quantify the cost of the wasted exergy necessary to support the workhours and to generate capital flows. In order to highlight the use of this quantity we can analyse a case, just analyzed from the exergetic point of view: the district of Alessandria. Alessandria is an Italian district of Piedmont region, which covers a surface of 3,560 km^2, with a population of around 440,613 people, including 190 municipalities, among which the administrative centre: the municipality of Alessandria. We analyze just the municipality of Alessandria, which covers 204 km^2 with a population of 93,922 people.

To do so, we apply the usual approach of engineering accounting, linking the prices of components to their operating parameters and to their exergetic efficiency, and pricing not the unit mass, but the specific exergy content of material or energy, by following the approach used in Reference [50], which consists in subdividing the country system into the following sectors:

1. Extraction, which includes mining and quarrying, oil and natural gas, refining and processing;
2. Conversion, which comprises heat and power plants;
3. Agriculture, forestry, fishery and related industries;
4. Industry, manufacturing industry except food industry and oil refineries;
5. Transportation services;
6. Tertiary sector, services other than transportation;
7. Domestic sector, households.

All fluxes between these sectors and between the surroundings and sectors within the system are being considered; each one of them is characterized as follows:

1. Resources: primary (fossil fuels, solar, wind, minerals, metals, geothermal, hydraulic) and secondary (products from petroleum refining, mineral and metal working) and electric energy;
2. Natural resources: agricultural products, wood, natural fibers, livestock, fish, game;
3. Products: products and services generated by industry, tertiary and transport sectors;
4. Trash fluxes: organic and inorganic waste materials, deposited in the environment;
5. Discharge: combustion gases, thermal discharge including radiated heat, heat and mass spread in the environment;
6. Human work.

Then, we develop the combination of exergetic and economic analysis by the definition of:

1. production cost of a system;
2. costs associated to losses;
3. performance of sectors or elements.

The data available for Alessandria are [32]:

1. The exergy inflow from the tertiary sector: it is distinguishing trait mainly from consumption of building headings, water systems and electrical appliances, from electricity you obtain low temperature heat, from fuels, which consists of Electricity 712 TJ (85% for low temperature heat) and Fuels 559 TJ, with a total amount of 1,271 TJ;
2. The exergy outflow from the tertiary sector uses: Electricity 289 TJ (low temperature heat 182 TJ, other uses 107 TJ) and Fuels 148 TJ, with a total amount of 437 TJ;
3. The exergy inflow from the residential sector: the consumptions of this branch are mainly for residential use for residential lightening, heating, etc.: Electricity 309 TJ and Fuels 2,825 TJ, with a total amount of 3,134 TJ;
4. The exergy outflow from the residential sector uses: Electricity 125 TJ (low temperature heat 79 TJ, other uses 46 TJ), and Fuels 992 TJ, with a total amount of 1,117 TJ;
5. The exergy inflow from the public transport: This sector receives in input fuel and in output mainly produces mechanical power: Electricity 14 TJ and Fuels 29 TJ, with a total amount of 43 TJ;
6. The exergy outflow from the public transport: Electricity 0 TJ, and Fuels 10 TJ, with a total amount of 10 TJ;
7. The exergy inflow from the private transport: This sector receives in input fuel and in output mainly produces mechanical power: Electricity 0 TJ and Fuels 2,230 TJ, with a total amount of 2,230 TJ;
8. The exergy outflow from the private transport: Electricity 0 TJ, and Fuels 652 TJ, with a total amount of 652 TJ;

with a total exergy inflow of 6,678 TJ and exergy outflow 2,216 TJ and an exergy lost of 4,462 TJ. By using the relation (13) we can evaluate the exergy inefficiency as 0.668. For Alessandria city, the number of worker in 2004 was 21,289, while the work hours per worker were 1819, so the indicator *EI* results 172 MJ/workhour. The equivalent wasted primary resource value results 115 MJ/workhour

Now, we can consider possible policy decision of the city administration, as follows:

1. introduce district heating: it would reduce
   - the exergy inflow for tertiary sector of electricity uses to 107 TJ for the electricity and to 0 TJ for the fuels;
   - of the 90% of fuels for the exergy inflow and outflow from the residential sector;
2. improve the public transportation: it would:
   - improve, for public sector, the exergy inflow to 100 TJ and the exergy outflow to 34 TJ;
   - decrease, for private sector, the exergy inflow to 1,400 TJ and the exergy outflow to 409 TJ.

The result of these two energy management decision is to reduce the exergy inefficiency to 0.338, with a better energy management. We can also compare this result with an economic indicator, for this case, the indicator *EI* results 52 MJ/workhour. The equivalent primary wasted resource value results 18 MJ/workhour.

It is clear that the equivalent primary wasted resource value allows us to obtain both economic and energetic information, in relation to the ability of a system or a process to be sustainable. Less is the value of the equivalent wasted primary resource value, more the process is sustainable.

4. Conclusions

Science and technology are considered fundamental to the growth and socio-economic development of countries; indeed, technological development has impact on income distribution, economic growth, employment, trade, environment and industrial structure [51,52]. At all levels, the role of science and technology is fundamental; scientific knowledge and technologies are the basis to challenge economic, social, and environmental problems, in order to avoid unsustainable conditions. The analysis of technological processes can be developed using a thermodynamic approach [53] for the whole system and for all its interactions both internal to the process, and external to the environment and society. The results consist of a quantitative evaluation of the flows of matter and energy which occur in the system and of the consumption rate of the available resources. This information can represent a fundamental support to policy planning and resource management [54].

In order to evaluate the technological level, and the advanced level of industrial processes, some indicators must be considered. Every company applies different production processes, which cause different carbon emissions or environmental impact, therefore as regards the environmental effects, the process itself results more important than the product obtained. In order to analyze both the environmental impact and the technological level acquired by the countries several indicators can be introduced. These can be defined as [53] “an aggregate, a quantitative measure of the impact of a ‘community’ on its surroundings (environment)”. It implies that:

1. The ecological indicators must be applicable to any “community”;
2. They are aggregated because it cannot be limited to a single individual;
3. They consider only the effects produced on the environment that surrounds the community under examination.

The related properties of the sustainability indicators can be summarized as follows:

1. They must be evaluated using unambiguous and reproducible methods under a well defined set of fundamental assumptions;
2. They must be expressed by a numerical expression whose results can be ordered in an unambiguous way;
3. They must be calculated on the basis of intrinsic properties of the community and of the environment;
4. They must be normalized in order to compare different communities or environments;
5. They must be defined on the basis of the accepted laws of thermodynamics.

The 1992 Earth Summit stipulated that countries at national level as well as governmental and non-governmental organizations at international level should develop indicators of sustainable development in order to support countries in making decisions on sustainable development [51].

In this paper, we wish to suggest a new indicator, the equivalent primary wasted resource value for the work-hour. This indicator is interesting because it link the exery cost per work-hour with the inefficiency of the system, allowing us to consider the cost of the wasted exergy for maintaining a process. An example of application has been developed on Alessandria municipality, a well-known case of interest for the difficulties occurred in the last ten year. The results agree with a previous analysis of the same case, developed in [32] only by using the exergy analysis.

Nomenclature

e	Specific energy (J kg^{-1})
E	Energy (J)
Ex	Exergy (J)
EI	Equivalent primary resource value for the work-hour (J/workhour)
h	Specific enthalpy (J kg^{-1})
$\dot{m}$	Mass flow (kg s^{-1})
n	Number
J	General flow (kg m^{-2} s^{-1})
Q	Heat flow (W m^{-2})
s	Specific entropy (J kg^{-1} K^{-1})
S	Entropy (J K^{-1})
t	Time (s)
T	Temperature (K)
V	Volume (m^3)
X	General force (J m^2 kg^{-1})
$\nabla\cdot$	Divergence (m^{-1})
∇	Gradient (m^{-1})
Δ	Variation

Subscripts

g	Generation
i	i-th element
in	Inflow
out	Outflow
λ	Wasted
0	Reference (environment)

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