Exergy based analysis of economic sustainability

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Abstract
Exergy is presented here as the physical prime-mover of economic systems, and an exergy based concept of value is proposed in this paper. The main exergy fluxes are identified as those carried by raw exergy (primary sources), raw materials, usable exergy and exergy embodied in manufactured commodities. It is shown how efficiency of exergy use is the physical basis for competitiveness and how exergy content (value) can be assigned to skillfulness and expertise. Sustainability of economic systems is analyzed in the light of competitiveness and ability to take extra exergy taken from markets. It is also shown that in competitive economies the ratio (raw exergy)/(total value) tends to decrease, therefore indicating extra exergy from the markets, and this trend is illustrated with the case of the US economy. Finally, the average electricity price in the markets was proposed as a provisional correspondence between exergy content and price of commodities.

1. Introduction

A key problem in economics is that of finding a sound base for the concept of value.

The first theoretical attempt is due to Adam Smith (1776) with his *labour* theory of value that located the source of wealth in the productive activity of the population rather than in the god-given fertility of land, as was accepted up till then. Further developments by Ricardo and Marx tried adding consistency and credibility to the *labour* theory of value, initiating a process that is still active at the present time - see (Foley, 2000) for a comprehensive review. In addition to the embodied labour theory, J. S. Mill (1806-1873, see Patterson, 1998) developed the idea of utility, which considers value as the degree at which some product is "desired" by the consumer. Mill's idea of value was further developed by Menger (1840-1921), Walras (1834-1910), Jevons (1835-1882) and is at the far origin of the so-called "neoclassical revolution" of Alfred Marshall (1842-1924) which sees the equilibrium price of a product as the point where the supply curve (marginal costs) and the demand curve (marginal utility) meet, the so-called "Marshallian Scissors" (see Petterson, 1998).

In the early sixties, Sraffa (1960) proposed a model of exchange of commodities based on physical quantities like mass and energy, the value of a commodity being determined by the exchange process and therefore being subjective rather than objective. A pertinent criticism to Sraffa's model is that it did not allow for conservation of mass and energy (Petterson, 1998).

More recently, some authors proposed an embodied energy theory of value in which energy is considered to be the fundamental factor that drives economic systems (Constanza, 1981; Lavine, 1984; Judson, 1989; Hall et al., 1992, Odum, 1996). Odum (1996) has put forward the concept of *emergy* as representing a measure of the value of a commodity based on the energy required to produce it.

The main problem with the embodied energy theory of value is the use of mixed units of value, i.e., value is based in both mass and energy flows that cross the economic systems (Patterson, 1998). In line with the embodied energy theory of value, Patterson (1983, 1993) developed the quality equivalent methodology (QEM) for commensurating energy flows in complex economic systems, which accounted for the process efficiencies of energy conversions. However, Patterson (1998) recognized that QEM had some difficulties in dealing with mass fluxes. The debate about the role of energy in economics continues lively (e.g. Keen, 2003; Ayres, 2002, 2003; Sousa and Domingos, 2005).

All these recent approaches recognize the key role of energy in determining the value of commodities. The problem here is to find out a common basis for expressing a socially and economically accepted concept of value.

In this paper we will tray to explore the physical concept of exergy as common basis for expressing the concept of value in an economic system.

2. Exergy based concept of value

It is a remarkable coincidence that all theories of value that have been considered so far use, in one way or another, the concept of energy (e.g., embodied labor, embodied energy, cost and utility that may be viewed as an expression of energy conversion, etc). Actually, energy is involved in all aspects of economics and it is well worth investigating to what extent it represents a common base for economic processes.

From a physical point of view it is easily recognized that all processes occurring on earth result in entropy production (energy disorganization) that corresponds to exergy destruction. *Exergy* is a measurable quantity that means useful energy, i.e. that amount of energy that can drive a process. Exergy represents the maximum useful work that can be extracted from a process in which a system is brought to equilibrium with respect to a reference environment. In this way, exergy is *value* because it opens the possibility of realizing useful processes, and ultimately the possibility of satisfying the human needs.

Food availability is essential for human survival and therefore food sources were historically a value for the first human societies. Dominance of territories that comprised food sources was a pursued objective. As soon as agriculture thrived and allowed increased food production, value was recognized to land as the source of wealth. At this stage, the human societies used the solar-earth radiation exergy stored in agricultural products for survival of the individuals and animal exergy for work and transportation.

In the XVIIL century, Adam Smith focuses on labor as the source of wealth, which corresponds to recognizing the increasing importance of the human intelligence and skillfulness in producing commodities. In fact, a skilled worker uses his intelligence to increase the efficiency and extent to which commodities are produced, therefore making better use of the available exergy sources. The increasing value of qualified work in modern societies stems from the fact that it allows achieving progress in process efficiencies therefore increasing competitiveness and economic development.

The previous conceptual framework makes clear that economic systems develop because association of individuals is more efficient in mastering exergy use that the individual itself. In this way, the activity specialization in a society leads necessarily to exchange of goods and services among the individuals, therefore establishing an economic system. This same principle of increased efficiency in mastering the available exergy sources in benefit of the individuals was at the origin of the animal societies that ever thrived on Earth. Living trees are also examples of economic systems in which chloroplasts, cells from the roots and the stem perform different activities and exchange substances that flow in the internal vessels for shared benefit of every part of the community. A common feature is that exergy is required in every process while being also a finite resource. In an economic system, exergy carries value because this resource, or the right to make use of it, may be exchanged among individuals. Finiteness and ability to be exchanged forms the basis of the economic value of exergy.

The main sources of the exergy available on earth come from solar radiation, fossil fuels, and nuclear fuels. More precisely, is the difference between temperatures at which solar radiation is emitted from the sun and radiated from the earth that creates a usable potential (exergy) i.e. that allows part of solar radiation to be used to drive processes on earth. Similarly, it is the oxidation potential of fossil fuels that represents usable energy (exergy), the same occurring with high temperature heat released in nuclear reactions.

Every process makes use of exergy with a certain degree of efficiency. By definition, efficiency is the ratio of the useful work delivered by a process to the raw exergy used in the process. The finiteness of the available exergy implies that the quantity of manufactured products increases with efficiency of exergy use. Therefore, mastering of exergy conversion has the result of increasing exergy availability. Said another way, exergy savings signify availability of physical exergy i.e. value. In this way, knowledge and expertise constitutes value because it may be expressed in physical exergy units. The degree of knowledge and expertise at which a society uses the available exergy is a measure of its technological development.

Going back in History it is known that the pre-industrial societies used land, or more precisely, plants as primary collectors and accumulators (food) of raw solar exergy. Animals were used as secondary exergy accumulators (food) and converters (work). The efficiency of these processes was very low therefore explaining why few extra products were available for exchange in the market. The first economic systems developed slowly also because the establishment of markets appeared late after millenniums of war with the purpose of pillage and spoliation. The raw exergy flux (ψ_{er}^{+}) available from incoming and outgoing solar radiation flux absorbed by the biomass q, (which is emitted from the sun at temperature T_s and radiated from the earth at temperature T_e) is given by:

$$\left(\psi_{er}^{+}\right)_{solar} = q\left(1 - \frac{T_e}{T_s}\right) \tag{1}$$

A small part η_{er} of the raw solar exergy flux ψ_{er}^{+} (Wm^{-2}) is converted into ex-

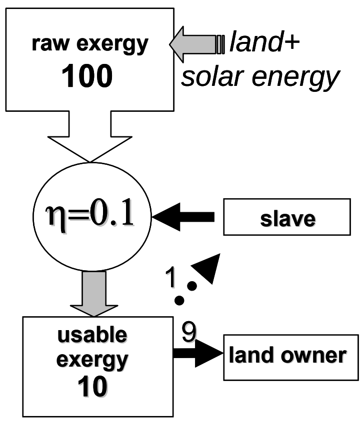

Fig. 1. Exergy conversion in a pre-industrial economic system.

ergy of the biomass by living plants, which can be used by animals for their needs:

$$\left(\psi_e^+\right)_{solar} = \left(\eta_{er}\psi_{er}^+\right)_{solar} \tag{2}$$

In such a society, due to the poor technology employed (usually slavish work) the efficiency of exergy conversion allowed little returns that were unequally shared between land owner and worker.

The continuous technologic developments achieved by modern societies have improved enormously the efficiency of exergy conversion. Efficiency is achieved through progress in knowledge, specialization, activity diversification and complexness of processes. In modern economic systems skilled workers contribute to efficiency of exergy conversion. Such workers need increased access and consumption of exergy so as to acquire skillfulness and expertise. Though they continue receiving a small part of final products, the increased production allows higher incomes (wages) than those of the pre-industrial period (Fig. 2). Actually, the logic of product sharing in modern societies is based on maintenance of skilled workers rather than in moral concerns.

2.1. Exergy/value fluxes in an economic system

In view of the key idea that every economic process involves the use of exergy we can draw a simplified picture of the main processes involving exergy fluxes and conversions i.e. that carry and add value to a commodity.

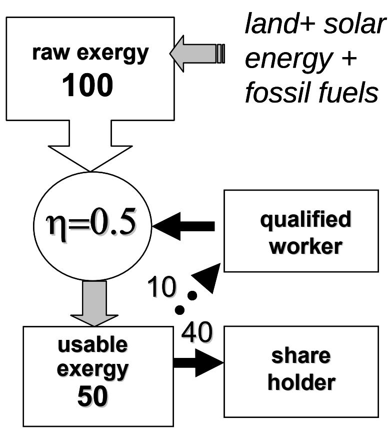

Fig. 2. Exergy conversion in a modern economic system.

Solar radiation, fossil fuels, and nuclear fuels comprise the main primary exergy sources (raw exergy - see Fig. 3). A fraction η_{er} of the available raw exergy is converted to usable exergy (see Eq. 2). As discussed before, the fraction η_{er} accounts for the efficiency of exergy conversion and stands for an index of technologic development. The amount ψ_e^+ of usable exergy is available as the prime-mover of all economic activities (transportation, industrial and agricultural activities, etc).

A part of the usable exergy (ψ_e^+) is destroyed in the extraction processes of raw exergy (oil, coal, etc). If ψ_{0er}^- represents the minimum work necessary for extracting a unit of raw exergy, then the usable exergy destroyed in this process amounts to $\left(\psi_{0er}^- / \eta_{er}\right)$, where $\eta_{er} = \psi_{0erl}^- / \left(\psi_{er}^-\right)_{real}$ stands for the efficiency of the process (see Fig. 4). On the other hand, the extractive industry workers (N_{er}) are paid on the amount $\theta\eta_{er}N_{er}$, where $\theta\eta_{er}$ expresses the assumption that that wages are proportional to efficiency η_{er}. The constant θ stands for the degree at which workers share the product (political index). The payment is understood as the acquisition of the right to purchase final services and products that carry embodied exergy on the market up to the amount $\theta\eta_{er}N_{er}$, which allow the formation and maintenance of the worker. In this way, the total exergy destroyed in the process of extracting raw exergy is:

$$\psi_{er}^- = \psi_{0er}^- / \eta_{er} + \theta\eta_{er}N_{er} \tag{3}$$

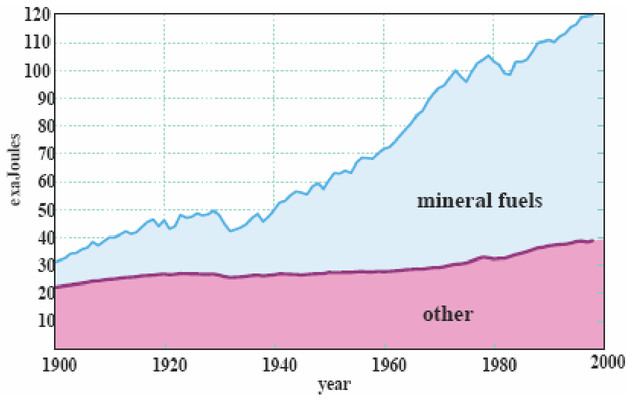

Fig. 3 - Raw exergy inputs to the US economy 1900 - 2000 (adapt. Ayres, 2003).

Extraction of raw materials from nature also involves the use of exergy (Fig.4). Therefore raw materials carry a value corresponding to the usable exergy that has been destroyed in the extraction processes. Similarly to the raw exergy conversion, the exergy destroyed in the extraction of raw materials is given by:

$$\psi_{mr}^{-} = \psi_{0mr}^{-} / \eta_{mr} + \theta \eta_{mr} N_{mr} \tag{4}$$

where the subscript m refers to raw materials.

Agriculture and manufacturing destroy usable exergy to produce commodities that therefore carry embodied exergy, which forms part of its value in the market (Fig.4). Analogously to the previous cases, the part of the exergy embodied in commodities corresponding to agriculture and manufacturing is given by:

$$\psi_{c}^{-} = \psi_{0c}^{-} / \eta_{c} + \theta \eta_{c} N_{c} \tag{5}$$

Finally, people involved in the conversion of raw exergy to usable exergy in energy plants (electric power plants, internal combustion engines, etc) are paid on the amount:

$$\psi_{e}^{-} = \theta \eta_{e} N_{e} \tag{6}$$

For physical reasons, the total usable exergy must be equal or higher than

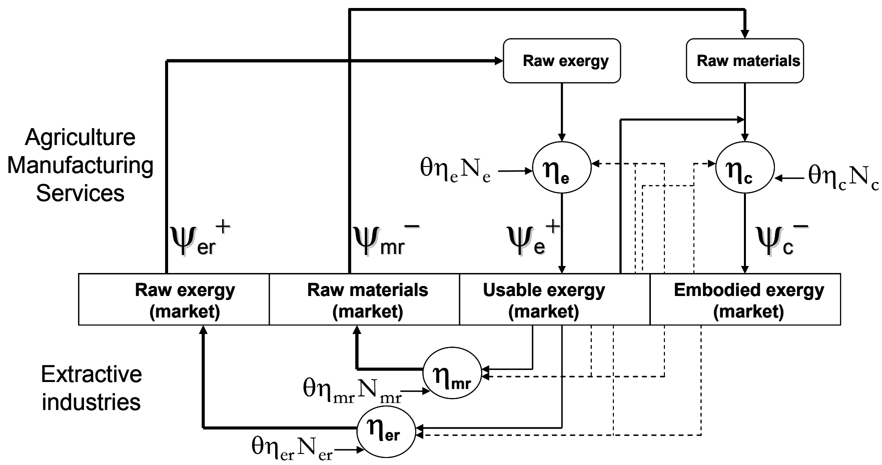

Fig. 4 – Main exergy fluxes in a modern economic system.

the total exergy embodied in all economic processes, i.e.

$$\psi_e^+ - \left(\psi_{er}^- + \psi_{mr}^- + \psi_c^- + \psi_e^-\right) = \Delta\psi_e \geq 0 \tag{7}$$

Economic systems achieve sustainability as long as $\Delta\psi_e \approx 0$ and grow if $\Delta\psi_e > 0$. In this way, eq. (7) expresses the inescapable constraint to which every sustainable economic system must comply with.

3. Competitiveness and sustainability

Efficiency of exergy conversion processes (economic processes) is crucial for competitiveness. In fact, if some commodity is sold in the market at the unitary price of $\bar{\varepsilon}_c = \bar{\psi}_{0c}^- / (\eta_c n_c)$, which represents the average of the total exergy embodied per commodity (total number n_c), and if some company is able to produce it at lower level of embodied exergy ε_c, then is able to produce this commodity at higher extent as compared with other competitors, and as a result, to get a surplus of other commodities from the market (higher exchange ratio). From this point of view, efficiency of exergy conversion is the basis for economic competitiveness. Therefore, competitive exergy users take exergy from the market and grow while inefficient exergy users loose exergy to the market (Fig. 5).

An ideal market should promote ideal competitiveness and selection of the most efficient exergy users. Actual markets are not ideal, in part because they are politically and socially constrained and in another part because market operators do not have full information and do not share it at the same extent.

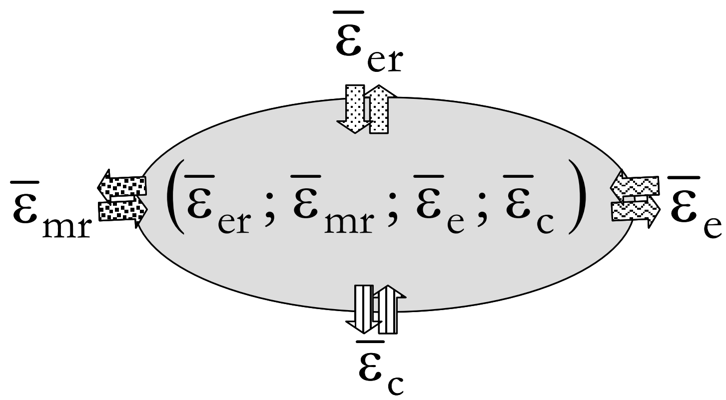

Fig. 5 – Competitive exergy fluxes (gains and losses) in an open market.

3.1. Competitiveness

A simple exercise illustrates how efficient exergy users can take exergy from the market. For the case of commodities, and taking into account eq. (5) we calculate the flux of exergy $\Delta\varepsilon_c = \overline{\varepsilon}_c - \varepsilon_c$ between a company and the market as:

$$\Delta\varepsilon_c = \left(\varepsilon_c - \theta\overline{\eta}_c\left(N_c/n_c\right)\right)\left(\Delta\eta_c/\overline{\eta}_c\right) \quad (8)$$

The sign of the exergy flux depends on the factor $\left(\varepsilon_c - \theta\overline{\eta}_c\left(N_c/n_c\right)\right)$ that accounts for the part in embodied exergy corresponding to wages. As $\left(\varepsilon_c - \theta\overline{\eta}_c\left(N_c/n_c\right)\right) > 0$, gain in efficiency leads to positive exergy fluxes, while the opposite occurs in case of decrease in efficiency. The case $\left(\varepsilon_c - \theta\overline{\eta}_c\left(N_c/n_c\right)\right) < 0$ cannot be considered because it would mean that exergy corresponding to wages would exceed the total exergy embodied in the product, and therefore the process would not be sustainable. A similar analysis can be carried out for raw exergy, raw materials and usable exergy.

As a general rule, a competitive system takes exergy from the market while a non-competitive system looses exergy to the market. A neutral system uses the proper exergy only.

The embodied exergy added to the product per worker $\psi^{-}/\theta N = k$ is a key factor in the exergy fluxes. The importance of this factor is shown in Fig. 6, where the curves correspond to graphical representations of eq (8) for dif-

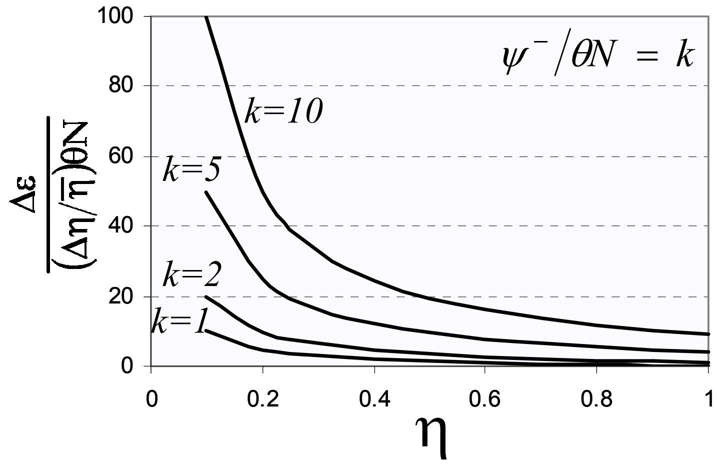

Fig. 6 – Exergy gains as function of efficiency, for various values of embodied exergy added to the product per worker.

ferent values of the variables. We can observe that increase in efficiency induce exergy gains that are higher when starting up from low efficiency levels, and increase with embodied exergy added to the product per worker.

3.2. Sustainability

The overall balance of exergy gains and losses in an economic system indicates the trend of the system either for development or for decline. By considering all components, this balance reads:

$$\Delta\varepsilon_{er} + \Delta\varepsilon_{mr} + \Delta\varepsilon_{e} + \Delta\varepsilon_{c} = \Delta\varepsilon \qquad (9)$$

If $\Delta\varepsilon \geq 0$ such a system is sustainable and my even grow if $\Delta\varepsilon > 0$. Therefore, eq. (9) represents the criterion for sustainability, i.e., a system that does not loose exergy to the market is able to survive and may develop providing that it is able to take exergy from the market.

The total exergy (embodied plus usable exergy) fluxes (eqs. 3 - 6) plus the overall exergy gains form the value generated by an economic system, which reads:

$$\Psi = \psi_{e}^{+} + \psi_{er}^{-} + \psi_{mr}^{-} + \psi_{c}^{-} + \psi_{e}^{-} + \Delta\varepsilon \qquad (10)$$

By using eqs. (2) and (7), the eq. (10) becomes:

$$\Psi = 2\eta_{er}\psi_{er}^{+} + \Delta\varepsilon \qquad (11)$$

which means that the value generated is twice the embodied exergy, plus the exergy taken from the market ((or loosen to the market). The fact that the usable exergy appears twice corresponds to the idea that in equilibrium ($\Delta\varepsilon = 0$) the system must be supplied with the same amount of exergy that is being continuously embodied in commodities.

From eq. (11) we can envisage that in a thriving economic system the exergy taken from the market corresponds to a large part of total value generated. By considering the ratio (raw exergy)/(total value), i.e.

$$\frac{\eta_{er}\psi_{er}^{+}}{\Psi} = \frac{1}{2} - \frac{\Delta\varepsilon}{2\Psi} \qquad (12)$$

we notice that this ratio must diminish with economic growth. Actually this trend is observed in thriving economic systems. If Fig. 7 we see that the ratio

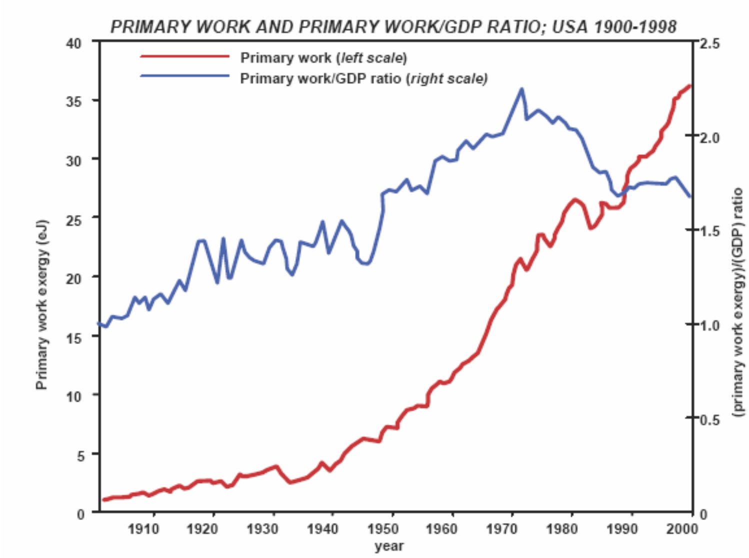

Fig. 7 – Decrease of the ratio (raw exergy)/(total value) since 1970 indicating that the US economy takes exergy from the markets due to its competitiveness in the global economy (Ayres et al., 2002)

$(\eta_{er}\psi_{er}^{+})/\Psi$ decreases continuously from the end of the sixties on, which corresponds to development of global markets (note that the scale on the right dos not uses the same exergy measure as in the present paper). The US economy has been able to take exergy from the markets at a high extent, not only because of competitiveness but also because of political domination (imperialism).

4. Measure of exergy fluxes

Measuring exergy fluxes is fundamental for developing a quantitative analysis of an economic system. Price is the actual, but imperfect and inaccurate measure of exergy in economics. Price is an estimate of the actual exergy usable or embodied in a commodity. This estimate results from the subjective evaluation of the exergy content (value) of a commodity by a large number of market operators. Because subjectivity is involved in the estimate, prices though not representing the real value of a commodity are supposed to approach it with a certain range of uncertainty. Therefore the need for a more objective measure of the exergy content is required.

A provisional correspondence between exergy content and price may be established based on electricity prices without the part corresponding to taxes. In fact, electricity is the most common form of usable exergy; it is widespread and is easily measurable. In this way, prices could provisionally be referred to a unit of energy (e.g. kWh, J(joule)). This correspondence should be established based on the average price of electricity in the open (unrestricted or less regulated) markets. Though provisional, this measure of exergy content would increase stability of price formation and would be grounded on physical basis. The evaluation of sustainability would be a credible criterion because it would be grounded on the realm of what really matters, i.e., the exergy balance of economic systems.

5. Conclusions

We proposed an exergy based concept of value and show how activities in economic systems may be described based on the exergy concept of value. Exergy is the physical variable that drives physical processes and its importance as the physical prime-mover of economic systems was identified and highlighted.

The main exergy fluxes in an economic system are: (i) raw exergy fluxes that account for extraction of primary exergy sources (e.g. crude, uranium, solar and environmental exergies); (ii) fluxes of exergy embodied in the extraction of raw material fluxes (minerals, organic and inorganic substances, etc.); (iii) fluxes of usable energy (e.g. electricity, gasoline, hydrogen, natural gas, etc.); and (iv) fluxes of exergy embodied in manufactured commodities.

The efficiency of exergy use in conversion processes determines competitiveness in the market. Skillfulness and expertise are recognized to play a fundamental role because they increase efficiency and exergy savings in the production of commodities, and therefore have exergy content (value). It is shown how competitiveness allows taking extra exergy from the markets allows development and growth of companies.

The basis of economic sustainability was established in relation with efficiency of exergy use. Companies on the rise take exergy from the markets and grow while non-efficient exergy users loose exergy to the markets and tend to disappear. It is also shown that in competitive economies the ratio (raw exergy)/(total value) tend to decrease in time, therefore indicating that they take exergy at ever-increasing extent from global markets, which was illustrated with the case of the US economy.

It was recognized that an accurate measure of value based on embodied exergy is still lacking. The average electricity price was proposed as a provisional correspondence between exergy content and price of commodities.

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