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Laws of thermodynamics and sustainability of the economy

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The consequences of mass and energy conservation and the laws of thermodynamics for economic activity are analysed. As the objectives, for this content of the relations between thermodynamics and economics is critically investigated. First, the relations between mass and energy conservation and the Laws of Thermodynamics are discussed. Then the analysis of neoclassical economics attitudes to the Laws of Thermodynamics is given. After this the analysis of the concept of weak sustainability and the Laws of Thermodynamics are discussed. Methods of systematic scientific literature analysis, general and logical analysis, comparison and generalization were used as the methods of the research.

The relation between Thermodynamics and Economics is a paramount issue in Ecological Economics. Basically, the Laws of Thermodynamics are relevant to the economy because economic activity is entropic. The integration between economics and thermodynamics at the substantive level is of crucial importance because economic processes obey thermodynamic laws and therefore a sound economic theory must be coherent with thermodynamics.

When applying a systems perspective to resources and environmental issues, it is natural to start with thermodynamics. Many resources and environmental problems have their roots in fundamental aspect of conservation of matter. When we analyzing the environment-economy interaction and taking economy, there in each stage of the production process waste will arise. The amount of waste in any period is equal to the amount of natural resources used. The reason for this equivalence is the First Law of Thermodynamics.

But some waste can be converted back to resources. Materials in goods can be recycled. But why not all waste is recycled? It is here that the Second Law of Thermodynamics become relevant. The materials that are used in economy tend to be used entropically and entropy places a physical obstacle, a 'boundary', in the way of redesigning economy as a closed and sustainable system.

In recent years a new discipline Industrial Ecology, has emerged. This new discipline has been built, to a large extent, based on perceived analogies between economic and ecological systems. But the essential ecological difference between people and other species is that, in addition to our ***biological*** *metabolism, people created enterprises with* ***industrial*** *metabolism. This stands as a crucial opposition to evolution of biosphere, which took many billions of years to evolve.*

Interpretations of strong and weak sustainability can also be justified by studying the possibilities of substituting supplies of nature's and economic capital or complementing each other. Strong sustainability requires both types of capital not to decrease for the benefit of one of significant indicators. The version of weak sustainability contains (making an unrealistic assumption about the perfect substitution of nature's and man-made capital) the sum of the forms of both capital – nature's and economic capital – or any other aggregated unit of measurement, and requires it not to decline all the time.

Keywords: *Economy; Mass and energy conservation; Entropy; Exergy; Laws of Thermodynamics; Sustainability; Neoclassical economics; Ecological economics*

Introduction

The Problem. The relation between Thermodynamics and Economics is a paramount issue in Ecological Economics. The question whether physical laws like the entropy law or the conservation laws of mass and energy are relevant to economic analysis has given rise to disputes. From the other side, the neoclassical economics which dominates resource and environmental analysis and policy is based on atomistic and mechanistic assumptions about individuals, firms, resources, and technologies which are inappropriate to the complex and pervasive physical connectivity of both natural and economic systems.

The Research Object. The main attention in the article is given to analyze the relation between thermodynamics and economics issues.

The Objective. The content of the relations between thermodynamics and economics is critically investigated in the article.

The Tasks. In order to fulfill these objectives, the following research tasks had to be accomplished:

To investigate the relations between mass and

- energy conservation and the Laws of Thermodynamics.
- To discuss neoclassical economics attitudes to the Laws of Thermodynamics.

- To investigate the concept of weak sustainability in the context of the Laws of Thermodynamics.

The Methods of the research. Logic abstraction, which encompasses generalisations on theoretical systems analysis of the environmental and ecological economics, according to the conclusions and reasoning of scientists from other countries was used in the article. The main scientific works related to the problem have been reviewed and thoroughly analysed.

Mass and energy conservation and the Laws of Thermodynamics

The relation between Thermodynamics (that part of physics which deals with conversions of energy and matter) and Economics is a paramount issue in Ecological Economics.

Generally, all systems are (at minimum) thermodynamic systems (in addition to their other characteristics) so that thermodynamic constrains and principles are applicable across both ecological and economic systems (Eriksson, 1991). This fact points out the need for a systems perspective on materials flows and the need to ask fundamental questions about the relationship between society and nature.

Basically, the Laws of Thermodynamics are relevant to the economy because economic activity is *entropic*. (*Entropy* is a measure of the disorder in a system, a highly organized system is said to be low-entropy, while a disordered system is said to be high-entropy. Entropy increases as order deceases. In this paper entropy will mean the tendency of matter and energy to degrade or disperse into less useful forms during economic activity). Economic production is utterly dependent on the availability of low-entropy inputs of natural resources (Daly and Cobb, 1989).

As shown by T. S. Domingos (2006), the integration between economics and thermodynamics at the substantive level is of crucial importance because economic processes obey thermodynamic laws and therefore a sound economic theory must be coherent with thermodynamics. This integration highlights the dependence between the economic system and the biophysical framework contributing to the analysis of the sustainability of economies, which are complex adaptive systems, that is, composed of large and increasing number of both components and of the relationships between them.

When applying a systems perspective to resources and environmental issues, it is natural to start with thermodynamics. Many resources and environmental problems have their roots in fundamental aspect of conservation of matter. As shown by D. W. Pearce and R. K. Turner (1990), when analyzing the environment-economy interaction and taking economy, there in each stage of the production process waste will arise. The processing of resources creates waste W_R, as with overburden tips at coal mines; production creates waste W_P in the form of industrial effluent and air pollution and solid waste; final consumers create waste W_C by generating sewage, litter, and municipal refuse.

The amount of waste in any period is equal to the amount of natural resources used *R*:

$$\mathbf{R = W = W_R + W_P + W_C} \quad (1).$$

The reason for this equivalence is the *First Law of Thermodynamics*. This law essentially states that we cannot create or destroy energy and matter, we can only transform it. In modern physics, matter itself is a form of energy, as is shown by A. Einstein's famous equation:

$$\mathbf{E = mc^2} \quad (2).$$

Whatever we use as resources, they must end up somewhere in the environmental system. It cannot be destroyed (Ayres and Kneese, 1969, Ayres, 1978). It can be converted and dissipated. For example, coal consumption in any year must be equal to the amount of waste gases and solids produced by coal combustion. Some of it will appear as slag, some as carbon dioxide and so on.

But we can take some of the waste, *W*, and convert it back to resources. *Closing the flow* of materials within society implies that the same asset or material is used again and again. We can *reuse* goods: we are all familiar with bottle banks for recycling glass bottles. Materials in goods can be *recycled* as with, for example, metals. Many metals (the metal in aluminum cans or the lead in lead-acid batteries) are recycled. Some waste paper returns to be pulped for making further paper, and so on. But a great deal of waste, indeed the majority of it, is not recycled.

Why not all waste is *recycled*? It is here that the *Second Law of Thermodynamics* becomes relevant. (This law was developed in connection with steam engines in 1824 by French physicist S. Carnot). The materials that are used in economy tend to be used *entropically* – they get dissipated within the economic system. Moreover there is a whole category of resources that cannot be recycled – energy resources. Entropy therefore places a physical obstacle, a 'boundary', in the way of redesigning economy as a closed and *sustainable* system.

So, there is another point of apparent similarity between ecological and economic systems that has attracted special attention in recent years, namely, 'recycling'. It is well-known that the industrial system is very wasteful of materials and recycles very little. Many well-meaning environmentalists seem to imagine that the biosphere is a perfect recycler and suggest that the industrial world should imitate 'nature' in this regard, i.e., to achieve 'zero emissions' in the industrial landscape by recycling all wastes. However, as shown by R. U. Ayres (2004), while most biomass is recycled fairly quickly, it is not true that there are no unrecycled wastes in nature. The idea of 'zero emissions' is based on the (false) idea that every biological waste is 'food' for some other organism. This is true, essentially, only for carbon-based organic materials and, especially, the well-known carbon-oxygen cycle. But the idea that some industry can always be found (or created) to consume another industry's waste, or even just its solid waste, is naive. In fact, 'zero emissions' from industry are only feasible in a few narrow and highly specialized contexts, primarily in the realm of food processing (Enzell et al., 1995). Recycling is another matter entirely, and a lot of industrial waste can be recycled, albeit not perfectly, and only by the application of significant amounts of energy (exergy) from somewhere outside the system.

Speaking about shortages of neoclassical economics, H. E. Daly (1995) argues that standard economics explains circular flows because they are mechanistic in nature (reversible and quality less) and that it does not explain the one-way flow of resources into waste because irreversible and mechanistic models cannot deal with irreversibility.

This irreversibility in processes and components depends on the energy degradation rate and not only on the ratio between the intensities of output and input flows, energy quality can be quantified by entropy analysis. Recently, several works have been published on the relation between exergy and environment (Rosen, 2002). Exergy is strictly connected to environmental impact, because pollution potential is proportional to the extent of energy conversion and utilization processes. Generally, exergy shows the value of energy as work, and permits comparisons between energies which are different from a Second Law point of view: it is defined by the maximum amount of work which can be ideally produced by a system as it comes to equilibrium with a reference ambient (Gong and Wall, 2001). In a real process, exergy consumption is related to entropy production due to irreversibilities, so the exergy takes into account the entropy increase in the environment due to the process: *the exergy loss is proportional to the entropy production*. Entropy is used as indicator of the sustainability of different areas from urban areas to agricultural zones; the entropy variations of a studied area are also used as a measure of the environmental pollution cost by the waste exergy approach to quantitative comparison of environment impacts. The Life Cycle Analysis method was initially based both on mass conservation and First Law of Thermodynamics. More recently the Second Law was considered and also an Exergy-based Life Cycle Costs Analysis (Ayres, 1998, Rosen, 2002).

Generally, as shown by F. C. Krysiak (2006), since the publication of the first economist who perceived the significance of *thermodynamic restrictions*, especially *the entropy law*, to the economic theory N. Georgescu-Roegen "The Entropy Law and the Economic Process" (Georgescu-Roegen, 1971), the question whether physical laws like the entropy law or the conservation laws of mass and energy are relevant to economic analysis has given rise to disputes. Two major positions have been developed.

The mainstream position has been formulated by R. M. Solow as "[…] everything is subject to the entropy law, but this is of no immediate practical importance for modeling what is, after all, a brief instant of time in a small corner of the universe" (Solow, 1997, p. 268). Thus mainstream economists acknowledge the existence of these laws, but they claim that these laws have no substantial consequences for economic analysis and can therefore be safely neglected.

This position has attracted much criticism, especially from ecological economists. H. E. Daly (1997) among others, argues that it is based on a misinterpretation of the entropy law and the conservation laws; in a form suitable for open systems, these laws do not only apply to the universe as a whole but to all systems that process mass or energy, including economic production and consumption activities. Furthermore, these laws have important consequences as they rule out the common model of a closed, nature-independent economy that can grow without limits.

H. E. Daly (1973) was among the first to introduce the issue of *permissible scope of economic activities* which was ignored by neoclassical economic theory (especially on the macro-level) in his works on the economy of *stationary status*. The author transferred the focus of economic research from *the economy of production scope*, reflecting effectiveness in changing scope of company or industry's production, to *the economy of scope*. His essential finding can be concluded as follows: *the economic activity should assume the intelligent (permissible) scope, reflecting ecological capacity of ecological systems* (Čiegis, 2004).

Seeing the environment as a complex ecosystem that is finite, non growing and materially closed (the exchange of matter with space is indeed very small compared to the flows on Earth), while open to a non growing, finite flow of solar energy, which is balanced by an outflow of energy in the form of heat radiation into space, and economy as an open subsystem forces to realize that consumption is not only disarrangement within the subsystem, but involves disarrangements in the rest of the system, the environment. As mentioned by H. E. Daly (1996), taking matter/energy from larger system, adding value to it, using up the added value, and returning waste, clearly alters the environment. The matter/energy we return is not the same as the matter/energy we take in. Common observation tells us, and the entropy law confirms, that waste matter/energy is qualitatively different from raw materials. Low-entropy matter/energy comes in, high-entropy matter/energy goes out, just as in organism's metabolism.

Since the work of R. U. Ayres and A. V. Kneese (1969) and of N. Georgescu-Roegen (1971) many studies have analyzed the consequences of thermodynamic laws for economic analysis. On the microeconomic level, Islam (1985) analyzes the consequences of the second law of thermodynamics, showing that it implies that the isoquants of a production process cannot comply with the often-used assumption of a Cobb–Douglas technology. On a macroeconomic scale, R. U. Ayres and A. V. Kneese (1969) have introduced mass and energy balances into static input–output analysis. Perrings (1986) has extended this analysis to linear dynamic models, showing that these balance equations can lead to instabilities. However, as shown by F. C. Krysiak (2006), mass and energy conservation alone, that is, without considering the second law of thermodynamics, does not challenge the fundamental concepts of economic analysis.

The possible consequences of the second law on a macroeconomic scale are subject to an ongoing dispute.

Some scientists argue that although the second law may have consequences on a microeconomic scale, it is not relevant on a macroeconomic scale because the earth is an open system that imports "low entropy" by solar radiation. Furthermore, the capability of human beings to innovate provides a way to defer possible negative consequences of the second law to an unforeseeable future or even to avoid them completely (Krysiak, 2006). But others argue that they are based on an inaccurate implementation of the second law of thermodynamics. Especially, they argue that all feasible production processes are subject to the laws of thermodynamics, so that innovation will not provide a means to escape the constraints imposed by these laws.

From the other side, as was shown by J. Martinez-Alier (1991), to see economy as entropic does not imply ignorance of the anti-entropic properties of life (or, in general, of open systems). This point must be made explicitly because the growth of "social Prigoginism", i.e., the doctrine that human societies self-organize themselves in such a way as to make worries about depletion of resources and pollution of the environment redundant.

N. Georgescu-Roegen (1971) developed a critique of standard economics from the standpoint of the second law of thermodynamics. But low entropy is necessary, but not a sufficient condition to transform matter into use-value. New science *bioeconomics*, based on the assertion that the economic process increasingly produces higher entropy that limits economic growth, centering its attention on the technological transformation of matter, suggests that entropy growth can be controlled by "social modeling" (Leff, 1996).

Neoclassical economics and the Laws of Thermodynamics

Economies are open complex adaptive systems far from thermodynamic equilibrium, and neoclassical environmental economics, which is based on atomistic and mechanistic assumptions about individuals, firms, resources, and technologies which are inappropriate to the complex and pervasive physical connectivity of both natural and economic systems, seems not to be the best way to describe the behaviour of such systems. In contrast to the materials-based approach of classical economic theory, neoclassical economics lacks any representation of materials, energy sources, physical structures, and time-dependent processes that are basic to an ecological approach. Worse, it is inconsistent with the physical connectivity and positive-feedback dynamics of energy and information systems (Christensen, 1991).

The belief that neoclassical economics is based on a formal analogy to classical mechanics and on isomorphism between the equations of mechanics and the equations of economic equilibrium of neoclassical economics after 1870 is common among ecological economists (Amir, 1995; Martinez-Alier, 1997; Costanza et al., 1997). Based on supposed analogy to classical mechanics, the main formal criticisms of neoclassical economics are: utility does not obey a conservation law as energy does; an equilibrium theory cannot be used to study irreversible processes. But T. S. Domingos (2006) argues that neoclassical economics is not formally identical to classical mechanics and that the correct identification of the formalism that underlies the construction of neoclassical economics is vital in the evaluation of its internal coherence. He shows that economics is formally identical to thermodynamics because they are both problems of static constrained optimization. However, it is of fundamental importance that the fact that neoclassical economics is formally identical to thermodynamics does not mean that it is compatible with thermodynamic laws.

It is generally claimed that neoclassical economics is based on classical mechanics because throughout the history of economics many economists used analogies from classical mechanics. As shown by T. S. Domingos (2006), this approach of establishing analogies between mechanics and economics was taken to its extreme by Irving Fisher who in 1892 established the most extensive relation between mechanics and economics. Given the history of economic analogies to mechanics, there is a widespread claim that neoclassical economics is fundamentally flawed because the assumptions on which classical mechanics is based do not apply to consumer theory. The most important aspects usually referred in the literature are: 1) utility does not obey a conservation law as energy does; 2) an equilibrium theory cannot be used to study irreversible processes. Some of the examples of this are described by T. S. Domingos (2006). He agreed that if neoclassical economics were indeed formally identical to classical mechanics it would be internally incoherent. However, he argued that neoclassical economics is based on a wrong formulation of classical mechanics, being in fact formally identical to thermodynamics. Both neoclassical economics and thermodynamics are equilibrium theories and can be developed as formalisms of constrained optimization.

However, it is of fundamental importance that the fact that neoclassical economics is formally identical to thermodynamics does not mean that it is compatible with thermodynamic laws. As shown by T. S. Domingos (2006), examples of flaws in the integration between economic theory and thermodynamic laws already identified are: economic theory considers a circular flow between households and firms without considering the one-way flow that begins with resources and ends with waste (Georgescu-Roegen, 1971); energy and capital are generally not substitutes, as assumed by production functions, but complements (Daly, 1997); and production theory does not fully possess thermodynamic irreversibility (Baumgärtner, 2005).

We would like to emphasize that the substantive integration between thermodynamics and economic systems should not be based on the thermodynamic theory of isolated systems. Economic systems are open thermodynamic systems far from equilibrium and therefore a thermodynamic analysis of economic systems should be based on the thermodynamics of non-equilibrium open systems (Kondepudi and Prigogine, 1998).

But *the neoclassical* model, assuming that nature is not involved in the production process and, consequently, production growth is not influenced by natural forces, *has separated the economic system from natural and other social systems.* It has concentrated exceptionally upon *value measures, such as*: *abstract labour* and *abstract capital invested*, totally ignoring their physical interfaces with the ecological sphere and functional qualities of utilised ecological systems. Therefore, the traditional *circulating economic model* was built upon the assumption that *economy* was the *whole* (but isolated) *system,* and *nature*- its *subsystem*. It described a closed, renewable system where natural resources and ecological systems were viewed as inexhaustible and renewable and primal factors, limiting economic development, were solely considered to be labour and capital.

This is also the economy which is self-sustaining. In neoclassical production theory, each input is assumed to be incrementally productive. Materials, energy, resources, physical connectivity, and the structures and organization of real world production are ignored (Christensen, 1991). Besides, another assumption is made in the traditional aggregated, homogeneous neo-classical *Cobb-Douglas's function of production*:

$$\mathbf{Y = A \times L^{a} \times K^{b}} \quad (3),$$

where: *Y* – national incomes, *K* – capital, *L* – labour, *a* and *b* are constants.

This *Cobb-Douglas's function* states that all production factors, limited and independent in nature, but *complementing* each other, can be *interchangeable or substituted* (Čiegis, 2004). Therefore, in such rare cases when the cost of natural resources (*R*) was reckoned in the *Cobb-Douglas's function* alongside with capital (*K*) and labour (*L*)- (for example, as suggested by *J. Stiglitz* in his aggregated production function), it was performed mathematically replacing *K* with *R*, where *R* equals zero, without any effect on the proportion of national income (*Y*).

Consequently, it was assumed that the capital created by man as the outcome of the technological changes could successfully replace the nature's capital on a regular basis, without any thermodynamic restrictions. These growth models never considered the fact that economies exist and are directly related to the biological world, which place restrictions to physical world. Eventually, it turned out that the economic models, which continue to ignore biological restrictions, are doomed, as they are hopelessly imperfect.

It is more obvious that we are dealing with complex natural-social systems, which no longer can be monitored within the classical paradigmatic framework of mechanics and engineering science. As was shown, biological and economic processes obey physical principles: the first and second laws of thermodynamics (conservation of energy and materials and the entropy law) and the principles governing individual material and energetic transformations (Ayres, 1978). These principles underlie the physical connectivity which characterizes biological and economic systems.

Thus, we need to replace the linear thinking about economic life with a more complex non-linear thinking, as well as we should apply a more holistic and evolutionary approach to economic activity, accepting ethic consequences of moral decisions, which we should make during the economic process. In fact, we need an analytical system, which could comprise ecological and social-economic systems. And the inputs of an ecological economics are not land, labour, and capital, but flows of materials, energy and information and the engines, machines, and workers organized to process materials, energy, and information.

Processes, occurring in the techno-sphere, are difficult to be explained according to the traditional economic paradigm, the direction of development which was determined only by interests of labour and capital economy as well as by the pursuit of maximum productivity. As mentioned by R. U. Ayres (1989, 2004), in recent years, new discipline, Industrial Ecology, (or Industrial Metabolism,) has emerged. This new discipline has been built, to a large extent, based on perceived analogies between economic and ecological systems. There is an attractive analogy between nature and industry, based on the similarity of natural functions and certain industrial activities. But the economic system is not closely analogous to an ecosystem. The one element that both biologists and economists might be able to agree on is that both biological and economic evolutions are equilibrium seeking processes. But, as shown by R. U. Ayres (2004), to be sure, the relevant definitions of equilibrium are quite different in two cases. In biology, as in physics, the notion of equilibrium is based on thermodynamics. Another approach would emphasize the accumulation of information or 'orderliness' in a sense that might be possible to define and quantify. However, equilibrium in economics is quite different. It is a hypothetical steady state in which supply and demand are balanced for every commodity (Arrow and Debreu, 1954). Economists, having proved many theorems about the existence of such a state and its properties, have felt constrained to postulate that economic growth occurs in equilibrium, although it does not and cannot.

As shown by R. U. Ayres (2004), the main (and crucial) difference between biological and economic perspectives on evolution can be summarized succinctly. Biological evolution is a very slow unconscious process driven by physical phenomena (e.g., mutation) and implemented by competitive reproductive strategies adapted to specific environmental 'niches'. Economic evolution is, of course, much faster than biological evolution. Moreover, it is entirely driven by conscious human decisions bearing little resemblance to mutation and adjustment via population dynamics.

A crucial condition of an industrial economy operating through time is its ability to obtain flows of low entropy energy and materials. As Alfred Lotka noted, any organism that discovers how to take advantage of unused energy running over a dam gains a selective advantage over other organisms (Christensen, 1991). The essential ecological difference between people and other species is that, in addition to our ***biological*** *metabolism*, people created enterprises with ***industrial*** *metabolism*. This stands as a crucial opposition to *evolution* of biosphere, which took many billions of years to evolve. Thus, the society, trying to achieve "*economic evolution*", should "take lessons" from the biosphere (Čiegis, 2004).

The concept of weak sustainability and the Laws of Thermodynamics

Literature analysis has shown that in a static setting, physical conservation laws and the second law of thermodynamics imply that economic activity is likely to depend critically on natural resources and on the ability of the environment to absorb generated emissions. Without either of these, no production or consumption is possible, except for goods that are produced and consumed by completely reversible processes. In a dynamic setting, the physical constraints imply that, even with the possibility to accumulate human or physical capital, more production of a good with non-vanishing marginal entropy production always necessitates more resource use.

Interpretations of *strong* and *weak sustainability* can also be justified by studying the thermodynamic possibilities of substituting supplies of *nature's* and *economic* capital or complementing each other (Čiegis et al., 2005). *Strong* sustainability requires *both* types of capital not to decrease for the benefit of one of significant indicators. In other words, according to *the law of strong sustainability, the aggregate physical quantity of nature's capital or general nature's capital (despite its type) and its value should not decrease and should be preserved for future generations*. (In a more stringent version of *very strong sustainability* stationary limitations should be already defined in the macro-economic level). In addition, according to criteria of strong sustainability, a supposition is made that nature's and economic capital are *complementary* in the production process rather than *substituting* (Costanza, Daly, 1992). Actually, it is recognised that some natural resources and services cannot be totally substituted as these forms of nature's capital supply vital services for all life-supporting environmental systems. The version of *weak* sustainability is more acceptable for dominating economic theories, oriented towards securing the status where "wealth does not decrease in the time lag" (Pearce, 1993). (In case we apply a more narrow approach of *very weak sustainability***,** then productivity potential of common economy would resume untouched to ensure constant consumption per person in a given time). The version of *weak sustainability* contains (making an unrealistic assumption about the perfect substitution of nature's and man-made capital) the sum of the forms of both capital – nature's and economic capital- or any other aggregated unit of measurement (for example, the "green" GNP). *So there is orientation to the stock of the capital, which we are living for the future generations, expecting that this capital stocks must be not lesser as have our generation* (Pearce, Atkinson, 1993).

So, as described F. C. Krysiak (2006), weak sustainability holds that each generation has the moral obligation to keep the total capital stock at least constant, where the total capital stock is comprised of the stocks of natural and produced capital. We can formalize this by defining a total capital stock *C* that is an aggregate of resource stocks x_i (comprised of the stocks of exhaustible and renewable resources) and the stocks of capital goods Z_i. Furthermore, such an aggregate is commonly taken to be a linear aggregate, that is, we have:

$$\mathbf{C} = \sum_{i=1}^{q+v} \beta_i x_i + \sum_{j=1}^{n} \gamma_j Z_j \quad (4),$$

Where: β_i and γ_j are constant weights attached to the different stocks.

This form of aggregation implies an infinite elasticity of substitution between the different stocks, that is, it is always possible to exchange one unit of resource stock *i* for β_i / γ_j units of capital stock Z_j leaving the aggregate *C* unchanged.

But the important questions are under which conditions this property does not devaluate the aggregate *C* as a measure for sustainability and whether these conditions are consistent with physical constraints.

In fact, the foundation of weak *sustainability* was made by *J. Hartwick* (1977; 1978) and his proposed idea of *compensation*, elaborating on nature's capital and its loss which should be compensated by the additional man-made capital or by the combination of man-made capital and nature's capital. If we mark the letters K_t, H_t and R_t as resources of physical, human and nature's capital respectively in time period t, the net value of changes in general capital resources will acquire the following expression (5):

$$I_t^N = \frac{dK_t}{dt} + \frac{dH_t}{dt} + \frac{dR_t}{dt}$$

If $I_t^N = 0$, then the country reserves its general capital resources and it is capable of securing its consumption level. This result was named after Hartwick as *"the Hartwick rule"*. It postulates that economic growth can be considered "sustainable", if the level of investment is higher than the value of extracted resources, constituting the *scarcity rent*, i.e. if $I_t^N > 0$. It means, that where the capital stock includes exhaustible or depletable natural resources, a necessary condition for the value of capital to be non-declining is that the rents deriving from resource depletion should be reinvested in reproducible capital to compensate for the user costs of depletion.

But much of the industrial countries' wealth came from the exploitation (sometimes liquidation) of natural capital, not only within their own territories, but also within former colonies, taking its territories carrying capacity. And, as mentioned by W. E. Rees and M. Wackernagel (1994), this persistent relationship is an inevitable consequence of thermodynamic law. The techno-economic growth and high material standards of developed countries require continuous net transfers of negentropy (exergy and available energy/matter) to the industrial center. Conversely, less-developed regions and countries must experience a net increase in entropy as natural resources and traditional social structures are dismembered.

Conclusions

1. The marginal analysis applied in neoclassical economic theory caused the correlation among economic production, consumption and equity as a whole and natural resources and ecological systems not to be properly assessed and evaluated.

2. The irreversibility of the real processes implies exergy destruction and waste flow to the environment.

3. From the point of the mainstream economist, a rigorous proof that the entropy law and the conservation laws of mass and energy matter for economic analysis is still missing.

4. Literature analysis has shown that the formal criticisms of neoclassical economic theory are wrong because they are either based on mixing up the substantive and formal levels or they are based on the wrong assumption that the microeconomic formalism is analogous to the classical mechanics formalism.

5. It is of fundamental importance that the fact that neoclassical economics is formally identical to thermodynamics does not mean that it is compatible with thermodynamic laws.

6. In the neoclassical Cobb-Douglas function of production the assumption is made that all production factors can be replaceable and substituted. Therefore, growth models here do not suggest that economy's functioning depends on the biological world, which eventually places restrictions on physical growth.

7. One of the most significant ecological and social challenges of today brought up to the new paradigm of economic development is the importance of evaluating industrial metabolism, envisaging the analogy between economy and environment on the material level.

8. A biophysical organizational approach to ecological economics starts from a recognition of the environmental, technological, individual and social sources and support systems of productivity.

9. The version of weak sustainability contains (making an unrealistic assumption about the perfect substitution of nature's and man-made capital) the sum of the forms of both capital – nature's and economic capital – or any other aggregated unit of measurement (for example, the "green" GNP), and requires it not to decline all the time.

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Termodinamikos dėsniai ir ekonomikos darnumas

Santrauka

Šiame darbe nagrinėjamas masės ir energijos tvermės bei termodinamikos dėsnių poveikis ekonomikai. Šiuo tikslu išsamiai išanalizuotas sąryšis tarp termodinamikos teorijos ir ekonomikos teorijos. Pirmiausia aptartas ryšys tarp masės ir energijos tvermės bei

termodinamikos dėsnių. Tada pateiktas neoklasikinės ekonomikos teorijos požiūris į termodinamiką. Po šios analizės aptartas silpno darnumo ir termodinamikos dėsnių sąryšis.

Darbe naudojama sisteminė mokslinės literatūros analizė, taip pat bendroji ir loginė analizė, lyginimo ir apibendrinimo metodai.

Sąryšis tarp termodinamikos ir ekonomikos teorijos yra ypač svarbus, kai nagrinėjame ekologinės ekonomikos teorijos klausimus. Iš esmės termodinamikos dėsniai yra tiesiogiai susiję su ekonomika, nes ekonominė veikla didina *entropiją*. Ekonomikos teorijos ir termodinamikos sujungimas realiame lygyje yra ypač svarbus, tai reiškia, kad ekonominiai procesai tenkina fundamentinius termodinamikos dėsnius, ir bet kokia gyvybinga ekonomikos teorija privalo būti suderinta su termodinamikos postulatais.

Kai taikome sisteminį požiūrį išteklių ir aplinkosaugos problemoms, analizę natūralu pradėti nuo termodinamikos klausimų. Daugelio išteklių ir aplinkos problemų esmė siejasi su fundamentiniu masės tvermės dėsniu. Kai analizuojame aplinkos ir ekonomikos sąveiką ir nagrinėjame ekonomiką, tai matome, kad kiekviename gamybos žingsnyje atsiranda atliekų. Kiekvieno laiko periodo atžvilgiu atsiradusių atliekų kiekis yra lygus panaudotų gamtinių išteklių kiekiui. Tai paaiškina *pirmasis termodinamikos dėsnis*.

Aišku, dalį atliekų galime perdirbti į naudingas žaliavas. Taigi medžiagos, iš kurių gaminami produktai, gali būti *pakartotinai perdirbtos*. Bet kodėl negalima taip sutvarkyti visų atliekų? Kaip tik čia ir svarbus tampa *antrasis termodinamikos dėsnis*. Gamyboje naudojame medžiagas *entropiškai*, todėl visos sistemos entropijos didėjimas yra fundamentalusis gamtos barjeras, neleidžiantis sukurti ekonomikos kaip uždaros ir *darnios* sistemos.

Nagrinėdami neoklasikinės ekonomikos teorijos trūkumus, straipsnio autoriai tvirtina, kad standartinė teorija paaiškina tik ciklinius srautus, kadangi šie yra mechaninės prigimties (grįžtami ir mažėjančios kokybės), ir negali paaiškinti negrįžtamo išteklių perdirbimo į atliekas tėkmės, nes jos negrįžtami ir mechanistiniai modeliai tinka tik grįžtamiems procesams modeliuoti. Šis procesų ir atskirų komponentų negrįžtamumas priklauso ne tik nuo santykio tarp įtekančių ir ištekančių.

Pasirodžius N. Georgescu-Roegen veikalui „Entropijos dėsnis ir ekonomikos procesai“, pradėta plačiai diskutuoti, ar tokie fizikos dėsniai, kaip masės ir tvermės ar entropijos, yra svarbūs ir ekonominėje analizėje. Susiformavo du svarbiausi požiūriai. Dauguma ekonomistų, besilaikančių vyraujančios ekonomikos teorijos požiūrio, pripažįsta šių dėsnių egzistavimą, bet teigia, kad jie neturi nors kiek didesnės reikšmės ekonominei analizei ir todėl gali būti ignoruojami. Šis požiūris sulaukė daug kritikos, ypač energingai tai darė ekologinės ekonomikos atstovai. Jie tvirtino, kad jis remiasi neteisinga entropijos ir tvermės dėsnių interpretacija.

Ekonomikos yra atviros, sudėtingos, prisitaikančios sistemos, esančios toli nuo termodinaminės pusiausvyros ir neoklasikinės aplinkos ekonomikos teorijos, kuri remiasi atomistinėmis ir mechaninėmis prielaidomis apie individus, firmas, išteklius. Skirtingai negu klasikinė ekonomikos teorija, grindžiama medžiaginiu požiūriu, neoklasikinėje teorijoje nėra jokių medžiagų, energijos šaltinių, fizinių struktūrų bei nuo laiko priklausančių procesų aiškinimo ir naudojimo, o kaip tik tai ir sudaro ekologinio požiūrio pagrindą.

Tarp ekologinės ekonomikos šalininkų populiarus požiūris, kad neoklasikinė ekonomikos teorija remiasi formalia analogija su klasikine mechanika bei vienareikšmišku sąryšiu tarp mechanikos ir ekonomikos pusiausvyros lygčių. Tačiau šiame straipsnyje parodoma, kad neoklasikinė ekonomikos teorija nėra net ir formaliai tapatinga klasikinei mechanikai ir kad teisingas apibrėžimas formalizmo, sudarančio neoklasikinės ekonomikos karkasą, yra gyvybiškai svarbus, kai vertiname šios teorijos vidinę darną. Tačiau tai, kad neoklasikinė ekonomikos teorija yra formaliai panaši į termodinamikos teoriją, nereiškia, jog ji yra suderinama su termodinamikos dėsniais.

Buvo parodyta, kad biologiniai ir ekonominiai procesai paklūsta fizikos principams: pirmajam ir antrajam termodinamikos dėsniams (masės ir energijos tvermės bei entropijos dėsniams) ir principams, valdantiems atskirų medžiagų ir energijos rūšių transformacijas. Šie principai ir sudaro fizikinio susiejamumo, apibūdinančio biologines ir ekonomines sistemas, pagrindą.

Pastaraisiais metais atsirado nauja disciplina – pramonės ekologija. Ši nauja disciplina sukurta labiausiai remiantis analogija tarp ekonominių ir ekologinių sistemų. Tačiau esminis ekologinis skirtumas tarp žmonių ir kitų rūšių yra tai, kad žmonės, šalia mūsų ***biologinio*** *metabolizmo*, sukūrė ir įmones su ***pramoniniu*** *metabolizmu*. Čia matome milžinišką skirtumą nuo biosferos *evoliucijos*, kurios formavimasis truko milijardus metų.

Stipraus ir *silpno darnumo* interpretacijos taip pat gali būti grindžiamos *gamtinio* bei *ekonominio* kapitalo atsargų pakeičiamumo ir vienas kito papildymo galimybėmis.

Stiprus darnumas reikalauja, kad *abu* nemažėtų kurio nors svarbaus indikatoriaus požiūriu. Tai yra, laikantis *stipraus darnumo taisyklės*, reikalaujama, kad *visuminis gamtinio kapitalo fizinis kiekis, arba bendro gamtinio kapitalo, neatsižvelgiant į jo tipą, vertė nemažėtų ir būtų išsaugota ateinančioms kartoms*. Drauge, vadovaujantis stipraus darnumo kriterijais, skirtingai negu silpno darnumo koncepcija, daroma prielaida, kad gamtinis ir ekonominis kapitalas gamybos procese labiausiai yra vienas kitą *papildantys*, o ne *pakeičiantys*.

Vyraujančias ekonomines teorijas atstovaujantiems ekonomistams yra priimtinesnė *silpna* darnumo versija, orientuota į būklės, kuriai esant „gerovė nemažėja laikui bėgant“ užtikrinimą. *Silpno darnumo* versija apima (darant nerealią prielaidą apie gamtinio ir žmogaus padaryto kapitalo tobulą *pakeičiamumą*) abiejų kapitalo formų – gamtinio ir ekonominio kapitalo – sumą ir reikalauja, kad šis nemažėtų laikui bėgant.

Faktiškai *silpno darnumo* versijos pagrindas yra *J. Hartwick* pasiūlyta *kompensavimo* idėja, teigianti, kad gamtinio kapitalo praradimas turi būti kompensuotas papildomu žmonių padarytu kapitalu ar žmonių padaryto ir gamtinio kapitalo kombinacija.

Raktažodžiai: *ekonomika, masės ir energijos tvermė, entropija, eksergija, termodinamikos dėsniai, darnumas, neoklasikinė ekonomikos teorija, ekologinė ekonomikos teorija*

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