EARTH'S AVAILABLE ENERGY AND THE SUSTAINABLE DEVELOPMENT OF LIFE SUPPORT SYSTEMS

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Summary

This article is devoted to analyzing the need to develop life support systems (LSS) and using these systems under the conditions of the twenty-first century. The underlying problem concerns the use of all kinds of natural resources, especially nonrenewable ones, and the growing negative impact of human civilization on the earth's environment.

In the first part of the article, the concept of a universal thermodynamic unit—available energy (exergy)—is analyzed. It is shown that applying this concept allows us to solve two fundamental problems. The first one is the "Vernadsky problem" of the objective evaluation of all the natural materials and energy resources of the earth by using universal units. The second problem involves the calculation of the thermodynamic efficiency of a given LSS and consequently the principal possibilities and limitations of an improvement in this regard.

Furthermore, the energy, entropy, and exergy balances of the earth are presented and analyzed quantitatively and qualitatively with reference to the possibilities and limitations of the matter and energy potentials of our planet for use in different LSSs.
In the second part of the article, the economic problems that are closely linked with LSS optimization and the prediction of future development in this field are considered. It is demonstrated that neoclassical economics (NCE) cannot solve all problems related to the objective analysis and outlook for LSS development under the new conditions of the twenty-first century. The concept of "natural price" is analyzed and several of its applications are discussed. It is shown that there are three goal-functions of the optimization of such systems, depending on the level of the problem.

In conclusion, the paths to an "ecological economy" that provides for reduced use of *neo-organic* resources and the renewal of natural organic resources, along with the corresponding future development of LSSs, are analyzed.

1. Introduction

At the start of the twenty-first century, development of the world economy has made humanity aware of the need radically to change the way it treats the natural environment. The days when our surroundings could be regarded as harboring inexhaustible stores of raw materials and, in parallel, treated as a garbage dump, are over.

Failure to understand or consider this fact leads to environmental degradation and a decrease in Nature's ability to sustain human life. Throughout history humanity has faced this problem to a variable extent, but now the situation is much more worrisome.

Nature's "buffering capacity" on a world scale is reaching its limits. If we do not intend to head "back to the cave", we must solve a single, but very complicated problem. That is, we must ensure that Earth maintains the ability to support the growing population based on modern living standards over time.

Failing this, humankind could face a very serious problem in the near future. We will have to decide what is worse: to perish as a result of the depletion of natural resources or as a result of filling our garbage dumps beyond capacity. It is clear that this prospect cannot be allowed to occur even on the local scale.

This "categorical imperative", as put forward by Immanuel Kant, is independent of all ideological and political factors. People ranging from scientists and political leaders through laypersons are becoming aware of this situation (although this awareness is coming about more slowly than might be expected).

We should also remember that, according to a UN prediction, the earth's population will increase from 6×10^9 in 2000 to 9×10^9 in 2050. It is also important to consider the unequal level of resource consumption in various parts of the planet. At present, the biggest segment of the earth's population, that is more than 80% of consumers, have an energy consumption level of less than 10% per capita, which contrasts sharply with that of developed countries. Additional complications may result from climate change, rising sea levels, soil erosion, the increased concentration of harmful gases in the atmosphere (such as CO_2), the thinning of the ozone layer, and so on.

The urgent need to solve these problems cannot be overstated. Using the term introduced into science by P. Teilhard de Chardin and developed by V. Vernadsky, one can say that we now face the need to preserve and develop the earth's "noosphere". This term denotes the complex of the earth's spheres that are transformed by human activities. The noosphere comprises an inorganic part—the lithosphere, hydrosphere, and atmosphere—and an organic part, or biosphere. All the life support systems (LSS) of humanity are entirely incorporated into both parts of this noosphere as integral components. It is necessary to define this term because it will be used and analyzed below. The term "life support systems" denotes all natural or human-engineered systems that meet the needs associated with sustaining present human life and culture into the future.

The functioning of LSSs involves two forms of interaction with the parts of the noosphere. The first form relates to the consumption of natural resources and the rational limits on their use. By contrast, the second form of interaction is defined by the ability of the earth's surroundings to absorb and assimilate all the emissions from the many LSSs.

The results of such interactions as a rule have a negative effect on both the inorganic and organic components of the noosphere. But the extent of this negative impact differs with respect to the inorganic and organic parts of the noosphere.

Analysis of the consumption of inorganic natural resources shows that difficulties may arise solely from the depletion of certain resources. But in the foreseeable future, taking into account the possibilities of both science and engineering, this situation should not cause serious negative complications. As for the consumption of organic natural resources, there is more cause for concern, because these resources are being used up and destroyed much faster than they are being renewed. The negative effects in terms of ecology call for extensive scientific and practical study.

Emissions of inorganic wastes create pollution problems, which provoke many very dangerous environmental impacts. In the near future these negative results will increase. The "buffering capacity" of the earth's noosphere has limits.

The cardinal problem is as follows: to provide for the harmonious development of the noosphere taking into account the earth's full capabilities to support such development.

The movement in this direction has already started. Its positive results are connected with the development and use of natural, engineering, economic sciences, and ecology. However, each of these fields generally applies different approaches and measures to solve its own specific problems.

In parallel with these efforts, the new situation requires that a complex, so-called "noosphere approach" be developed in all the sciences connected with the interactions between LSSs and the natural surroundings. This is especially true with regard to the economic and ecological sciences. Failing this, irresolvable problems are bound to arise. Sophisticated problems call for complex integrated solutions. For example, where the problem of energy supply has to be solved in a given region, this seemingly local problem will present many potential solutions that could apply to a wide range of differing problems.

Primarily, there are several types of power station (thermal power plants based on the use of coal, oil, or nuclear fuel; hydroelectric plants; wind power stations). To make a choice, it is necessary to take into account not only the level of demand associated with different electricity and heat consumers, but the whole range of problems connected with the region's ecology: air, soil, and water pollution.

All the above-mentioned problems are merely "the tip of the iceberg". Any fuel (as well as all other materials for building and operating a power station) that is extracted, processed, and transported inevitably has negative effects on the environment. Any decision made without taking these different links into consideration cannot be optimal from the point of view of modern ecology. It is impossible to solve these different problems by purely monetary economics-based methods.

This situation gives rise to the need to have some generalized quantitative characteristics that could be used to measure the value of the different natural resources and the products resulting from their processing. This type of measurement is dependent on all economic and political fluctuations. It was the Russian scientist V. Vernadsky who pointed up the need to develop such characteristics in 1928. He wrote: "We still do not have a general measure that is the unified unit for the quantitative comparison of all natural productive forces; we should develop such a unit but it must be suitable for dealing with the energy patterns of human surroundings judging from the standpoint of life support."

It is obvious that such a measure, which may be called "absolute resource", could be based only on the most fundamental concepts of matter and energy. These notions alone make it possible to take an inventory of all the useful parts of the earth. But this, as undoubtedly the thesis corrects, is far from being a practical solution to the problem. This approach states only the region and direction of decision searching which would take several decades.

The main difficulty lies in the fact that such fundamental concepts as matter and energy cannot be directly used for creation of such a general measure. Matter can be used as an absolute resource because the latter concept incorporates the notion of a substance, which can be used up or depleted. (The word "substance" originates from the Latin word *substantia*, which signifies the ultimate reality that underlies all outward manifestations and change.) But matter, in accordance with the law of conservation, cannot be destroyed in principle. Accordingly, the amount of every type of matter on the earth must remain constant. "Loss of matter" is only a relative term, any "lost matter" can be returned over and over again to its original form through proper energy expenditures. Water and air can be regenerated, oxides reduced, wastes transformed into useful products. Besides, such an "absolute measure", according to Vernadsky, must reflect not only quantitative characteristics of each resource, but its quality in the context of practical use. This cannot be done using units of mass.

The second concept, that of energy, is less fundamental than matter, but gives greater hope of solving this problem. This is expressed by the apothegm: "The nature of energy lies at the heart of the mystery of our existence." S. Kapitsa wrote more specifically: "Energy is the main factor determining the production of food, support of industry and transport, the general wellbeing of humans and the security of societies." In principle, this is correct, because in the long run all problems related to the LSS and its interactions with the earth's surroundings are connected with energy and its transformations. Nevertheless, energy cannot be used directly as an "absolute resource".

Strangely enough, the law of energy conservation is a barrier here too (as with the law of matter conservation). Strictly speaking, it precludes the use of common expressions like "energy losses" and "energy expenditures" because energy, like matter, cannot be destroyed. In spite of this, a solution has been found.

Overcoming this stumbling block required a new approach, one based on both quantitative and qualitative characteristics pertaining not only to energy but to matter as well. Indeed, what is lost (destroyed) as a result of human activities, if quantities of matter and energy are not changed? All the used resources, in the long run, are transformed into various wastes. Fuel is transformed into fuel ash, slag, and smoke; biological products into organic wastes; and atmospheric oxygen into carbon dioxide. High-quality electrical energy, produced through transformation processes from chemical or nuclear fuel, dissipates into the environment as low-temperature heat. Everywhere the existence and action of life support systems inevitably lead to an irreversible dissipation of matter and energy. But all transformations result in the loss of quality!

The scientific analysis of all the processes connected with energy and matter transformations is dealt with by thermodynamics. Reliability of the results of its correct use (it is very important in this case) was demonstrated by Albert Einstein. He wrote: "A theory is more impressive the greater the simplicity of its premises, the more different are the kinds of things it relates, and the more extended its range of applicability. Therefore the deep impression that classical thermodynamics made on me. It is the only physical theory of universal content which I am convinced, that within the framework of applicability of its basic concepts will never be overthrown."

However, the classical thermodynamic apparatus did not lead immediately to the solution of practical problems connected with unified units, "absolute resource", though it has the general quality measure, entropy, which reflects the irreversible dissipation of energy. The main point is that, in classical thermodynamics, there is no concept of environment in the broad sense of the word. Classical thermodynamics operates only with concepts of the temperature of the environment, without considering other parameters (pressure, chemical composition). It is obvious that, without introducing such complex notions into thermodynamics, all the problems of various life support systems, operated in intimate connection with environment, cannot be solved. As a result of long investigations based on incorporating the concept of the environment into thermodynamics, a general concept was conceived. First, it was called "available", "free" energy, or "availability" (J. Keenan, 1932). Now this thermodynamics function is known as *exergy*. The term was coined (Z. Rant, 1956) from ex ("external"), and erg (Greek *ergon*, "energy").

On the basis of the "exergy approach", it is possible to develop on a practical level "the quantitative comparison of all natural productive forces" as discussed in works of V. Vernadsky. In other words, the universal measure came into being not only for primary energy supplies but also for all the resources that are necessary for human life support. Moreover, such a measure made it possible to analyze quantitatively production processes, evaluations of alternative technologies and perfectly all the life support systems, transforming all the natural resources into a very useful product.

Nowadays, objective analysis of this type is performed through the well-grounded estimation of matter and energy. The introduction of the concept of exergy provided the possibility of creating links between thermodynamics, economics, and ecology. Such "hybridization" opens up new possibilities for all these sciences.

With regard to economics, even neoclassical economics (NCE) does not deal adequately with externalities such as environmental contribution, resource values, waste minimization, and recycling. Conventional NCE cannot deal with critical time-dependent issues such as depletion of resources or changes in the conditions of the global life support system. Furthermore, all variants of NCE cannot predict the macroeconomic dynamic and business cycle turning points. With regard to ecology, the NCE model fails completely to capture the biophysical basis that enables every economy to function.

It is quite natural that present-day economics should also take into account the exergy approaches to all these complex problems. Accordingly, economic science encompasses a special branch based on the exergy approach. It goes without saying that this branch, called thermoeconomics or exergoeconomics, does not supplant modern-day economics in any way. However, the thermodynamic approach can make an essential contribution to economics, and can provide support for solving both the global and partial problems connected with life support system sophistication and future development trends.

In the second part of this article, the concept of available energy (exergy) is analyzed as a universal thermodynamic unit as applied to the two fundamental problems:

(a) the objective evaluation of all kinds of natural resources; and
(b) calculating the thermodynamic efficiency of any LSS and, consequently, the principal possibilities and limits of its improvement.

In the third part, the energy, entropy, and exergy balances of the earth are given and analyzed quantitatively. Consideration of these balances is conducted in the context of possibilities and limits of matter and energy potentials of our planet for application in various LSS in the near future.

In the last part of the article, economic problems that are closely linked with LSS optimization and prospects for their future development are considered. It is shown that there are two basic goal functions of optimizing such systems. The areas of application and conditions governing the application of these functions are discussed.

The conclusion briefly outlines ways of achieving an "ecological economy" and developing LSSs, in keeping with the goal of preserving the earth and nature.

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Biographical Sketch

V. Brodianski was born on 16 March, 1919, in Russia. He was educated at the Moscow Institute for Chemical Machinery (1937–41/46), and was a member of the Group of Cryogenic Engineering headed by P. Kapitza. Studies here were interrupted by service in the Soviet Army (1941–1945). He later took a postgraduate course at the Institute of Oxygen Machinery, Moscow (1950–1954), and was awarded the

SC degree of Candidate of Technical Science (1954). In 1967 he became Doctor of Technical Science, and the following year, Professor. His industrial experience dates back to his appointment as Chief of the Air Separation Department at the Moscow Autogenous Factory (1951–1957). Since 1955 he has served as chairman of the State Expert Councils and as an expert to the various state projects on energy and refrigeration. He is a member of the editorial boards of the Russian journals *Refrigerating Engineering* and *Refrigerating Business*. Since 1957 he has taught at the Moscow Energetic Institute (MEI, Technical University), being appointed docent in 1958 and professor in 1968. His main subject areas are low-temperature thermodynamics, the thermodynamic basis of refrigeration and cryogenics, and exergy and exergoeconomic analysis. All these have been the subjects of numerous lectures delivered both at home and in many other countries, and his contributions have been honored by various institutions. On the international front, he has served as a member of the Commission A-2 of the International Institute of Refrigeration (1972–1975); a member of the Scientific Committee of ENSEC-92 and ENSEC-93 (International Conference on Energy Systems and Ecology), and ITEC-95; and as a member of E-Group (European Working Group of Energy and Resource Conservation), ECOS-98.