Thermodynamic indicators for integrated assessment of sustainable energy technologies

A. V. Chamchine[1], G. M. Makhviladze[1] and O. G. Vorobyev[2]

[1] *Research Centre, Department of Built Environment, University of Central Lancashire, Preston, UK*

[2] *Department of Energy Installations and the Environment, St. Petersburg State Marine Technical University, St. Petersburg, Russia*

Abstract The development, state-of-the-art and application of exergy concept to sustainability are discussed. Thermodynamic indicators, based on exergy, are proposed for the design and optimisation of energy systems. Efficiency of energy systems is determined using energy and exergy. This paper presents a methodology study of thermodynamic indicators for integrated sustainability assessment and its application to geotechnic system analysis. Information, obtained from thermodynamic indicators, is proposed to be used for managing the natural resources and reducing the environmental degradation caused by interaction between an energy system and environment. Life cycle analysis on the basis of exergy flow calculations is considered for assessment of total environmental impact on all stages of energy system life cycle. Integrated exergetic assessment, based on exergy analysis and thermoeconomics, is recommended for comparisons of alternative technical solutions and decision making for energy system design. Application of thermoeconomics to sustainable buildings is examined.

Keywords energy; exergy; thermodynamic indicators; sustainability and sustainable buildings

1. Introduction

Sustainability is a new and rapidly growing multidisciplinary area. Solving environmental problems is a great challenge to human ingenuity. Main issues of sustainability include physics, engineering, ecology, economics, law, social science and politics.

Despite recent significant achievements in promoting sustainable life style there is no fundamental theory of sustainability. Behaviour of a system in terms of sustainability will be measured through the use of indicators. The main aim of this paper is to develop thermodynamic indicators for integrated assessment of sustainable energy technologies.

The modern period has been marked by sharply increased environmental problems both globally and in specific regions, where the issues are particularly acute. The negative consequences of human activities continue to generate ecological problems, reflected in a growing wave of demands for the adoption of prompt remedial measures. Unfortunately, such calls frequently do not be more than reiterate the necessity for environmental protection and lead at best to isolated and partial successes, most typically in blocking the construction of some environmentally dam-

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aging plants. It is significantly more difficult to tackle problems associated with already established industrial objects, especially if they are obviously profitable. The roots of the problem can be traced to a lack of ecological awareness in the planning of industrial projects.

There is inadequate appreciation or even total ignorance of the fact that an industrial object by itself constitutes a unique proactive and reactive factor. Such an object transforms the substance of nature, generates mass-energy fields and produces local environmental stresses capable of creating regional and in extreme cases even global tensions.

It is necessary to move from the planning of discrete industrial object to the planning of geotechnic systems (GTS) with adequate prognoses of the situations, which may in practice arise through the interplay of man-made and natural factors. In this paper assessment of GTS, formed by an energy plant, is considered.

2. Exergy analysis

To assess environmental effects in the GTS integrative system-level indicators are needed. Different environmental indicators are available, but they mainly integrate sectorial aspects only (i.e. monitoring). Systemic indicators are rare. Thermodynamic indicators, based on exergy analysis, are proposed for holistic assessment of energy technologies in the GTS.

Exergy, also known as availability, is defined as the maximum amount of work, which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy is a measure of the potential of the system or flow to cause a change, as a consequence of not being completely in stable equilibrium relative to the reference environment.

Exergy is conserved only in reversible processes. Due to the irreversibility of real processes, the work obtained is always less than the maximum work and exergy is destroyed. Thus, unlike energy, exergy is generally not subject to a conservation law. The exergy destruction during a process is proportional to the entropy created due to irreversibilities associated with the process.

Particularly, in energy systems the exergy of an energy carrier is a thermodynamic property that depends on both the state of carrier being considered and the state of the environment. It expresses the maximum capability of the energy carrier to cause changes [1]. Therefore, exergy is closely related to the economic value of the carrier because energy users pay for its potential to cause changes. Additionally, exergy is an additive function, because different exergy flows are compared on the same basis of reference environment.

The exergy E_ε contained in a system may be written as

$$E_\varepsilon = S(T - T_0) - V(p - p_0) + N_k(\mu_k - \mu_{k0}), \tag{1}$$

where the intensive properties are as follows: T – temperature, p – pressure, μ_k – chemical potential of substance k; and extensive properties are as follows:

S – entropy, V – volume, N_k – number of moles of substance k. The subscript ‘0’ denotes conditions of the reference environment.

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It follows from equation (1) that the exergy of system is zero, when it is in equilibrium with the reference environment: $T = T_0$, $p = p_0$, and $\mu_k = \mu_{k0}$ for all k.

Thus, exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy systems. The concept of exergy is simple, understandable and consistent with needs of sustainability.

Review of exergy analysis development and its application in optimisation of energy systems is given in [2]. In this paper main works in application of exergy to environment assessment are reviewed.

Szargut introduced the application of exergy for economic analysis [3, 4]. He suggested that the index of cumulative consumption (the loss of exergy of deposit resources) can be redefined as an index of ecological costs [3].

Brodianski in [5, 6] suggested exergy as an important parameter for complex technical, economic and environmental optimisation of energy systems. Jorgensen and Major in [7, 8] proposed to use exergy as a key function for ecological modelling. Wall in [9] proposed the use of exergy of emissions as an indicator of environmental effect. Yantovski further developed principles of an exergy technical, economic and environmental optimisation [10].

Exergy was introduced into methodology of environmental assessment and life cycle analysis in [11–18]. Exergy analysis was done for different areas of industry [19–22] and even for whole countries [23–25].

Nowadays, the exergy analysis has become accepted and used in some industries. However, there is still a gap between engineers and academics in understanding of an application of exergy analysis for technical, economic and environmental issues.

Recent papers [26–30], published in the International Journal of Exergy have showed that the concept of exergy successfully links the fields of energy, environment and sustainability. Thus, exergy is gradually being adopted as a useful tool in the development and design of a sustainable society. Let us consider the application of exergy flows as indicators of sustainability in a GTS.

3. Thermodynamic indicators of sustainability in energy systems

Exergy analysis of a GTS characterises its thermodynamic conditions, which present important information for assessment and optimisation. Exergy plays a part of thermodynamic quantity, which encapsulated the energy and entropy of a flow through a GTS. For GTS analysis, energy is a measure of quality, but exergy is a measure of both quality and quantity [6]. Exergy has more information aspect than energy, but it is generally more difficult to calculate exergy flows in comparison with energy ones. The Poiting vectors for energy and exergy flows are correspondingly as follows [10]:

$$\delta = \varphi \cdot j_q + \upsilon \cdot j_p + G \cdot j_m + T \cdot j_s, \tag{2}$$

$$\delta_\varepsilon = \varphi \cdot j_q + \upsilon \cdot j_p + G_\varepsilon \cdot j_m + (T - T_0) \cdot j_s, \tag{3}$$

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where φ – electrical potential; υ – velocity of movement; G – chemical potential (Gibbs function); G_ε – chemical exergy potential; T – temperature (thermal potential); j_q – density of electrical current; j_p – density of impulse flow; j_m – density of substance flow; j_s – density of entropy flow.

Changes of G to G_ε before density of impulse flow and T to $(T\text{-}T_0)$ before entropy flow are defined differences between equations (2) and (3). There is no saving law for density of exergy flows due to irreversible processes in a GTS.

It is proposed to use both energy and exergy characteristics for GTS analysis. Each GTS object is assessed by two efficiency coefficients – energy η and exergy η_ε:

$$\eta = \frac{E_p}{E_s}, \tag{4}$$

$$\eta_\varepsilon = \frac{E_{\varepsilon p}}{E_{\varepsilon s}}, \tag{5}$$

where E_p and $E_{\varepsilon p}$ are energy and exergy of products generating by the object; E_s and $E_{\varepsilon s}$ are supplied energy and exergy to the object.

GTS as a whole is characterised by total energy and exergy efficiency coefficients. Energy and exergy flow diagrams can be plotted at the final stage of calculations.

Exergy destruction in the GTS can be calculated either from total exergy balance of the system or from entropy production D using the Gouy and Stodola theorem:

$$D = T_0 \sum_i S_i, \tag{6}$$

where $?_0$ is temperature of the environment; S_i is increase of entropy in i object of the GTS.

By analysing energy and exergy losses within a GTS, imperfections can be pinpointed and quantified, and possible improvements suggested. This will increase GTS efficiency and reduce losses of availability (internal exergy destruction by imperfections and waste exergy). Important issue for GTS optimisation is an additivity of exergy flows. For example, for a GTS with combined heat and power systems it is difficult to estimate costs of cogeneration products. Within the scope of exergy analysis, these products are directly compared and exergetic production costs are applied. This exergetic method has as objective the minimum (optimal) total operating costs of cogeneration plant, assuming a fixed rate of electricity and process steam [31]. Such cost ratio of steam to electricity will be most probably different in comparison of the current selling prices, used by energy companies, but they have to know the real cost of generating different form of energy.

Generally exergy analysis provides an opportunity for united technical, economic and environmental optimisation on the basis of exergy calculations. In practice, the GTS optimisation is made by modelling and computer simulation studies.

It is worth to mention that exergy calculations have regional and season aspects, because exergy depends on environmental conditions (temperature of the local environment could be considered as only condition for many GTS). Values of exergy

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flows are different for different part of a country, especially for a big one like Russia, China or USA. Season changes of temperature can also play an important part for efficiency improvements. For example, in buildings different calculations of water and heat exergies could be applied in summer and winter conditions and different exergetic costs could be used.

Therefore, exergy is the most general expression of thermodynamic potential and it relates to the local environment. Exergy is better related to the environmental effects then energy, which makes exergy flows better as indicators of sustainability. For example, if a GTS finally consumes more exergy flows, including environmental protection measures, than it generates it is not sustainable. On global scale if a GTS, formed by a city or a country, consumes the exergy resources faster than they are renewed, it is not sustainable.

It is suggested that exergy as a special thermodynamic potential characterises environmental danger, since exergy determines work, which will be done in the local environment. Exergy indicators, based on rigorous thermodynamic calculations, can be used to improve the resource use and to reduce the environmental degradation.

An indicator of sustainability should be easy to understand and an unambiguous quantity. Within the Organisation for Economic Co-operation and Development the following definition is used: an indicator is “a parameter, or a value derived from parameters, which points to, provides information about, describes the state of phenomenon/environment/area, with a significance extending beyond that directly associated with a parameter value” [32].

There are many definitions of sustainable development or sustainability made by different organisations and individuals. The most commonly used statement of sustainable development was defined by the World Commission of Environment and Development as follows: “. . . development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [33].

The Engineering and Physical Sciences Research Council of the UK considers four dimensions to sustainable development: (i) effective protection of the environment; (ii) maintenance of high and stable levels of economic growth and employment (creation of new markets and opportunities and cost reductions through resource efficiency); (iii) prudent use of natural resources (reduced waste and effluent emissions, reduced impact of human health, use of renewable raw materials and elimination of toxic substances, recycling and recovery of materials); and (iv) social progress that recognise the needs of everyone (employee health and safety, reduced negative impact on quality of life in communities and equality of opportunity and benefits to disadvantaged groups).

Exergy concept directly relates to the first three dimensions and provides a significant information about resource efficiency, technologies, environmental impact, waste generation, life cycle costs and etc. It is possible to use exergy concept for the fourth dimension to sustainable development, as it was done using moral issues of exergy in [9]. Thus, exergy indicators meet the above-mentioned requirements and they can be used for assessment of sustainable technologies in different forms depending on GTS type.

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For GTS – "energy system and its environment", exergy indicators of GTS load into the environment during fixed time τ (stationary regime of energy system operation) are exergy flows of waste per square or volume of the surrounding environment:

$$i_{F,\tau} = \frac{\sum E_w}{F} \quad i_{V,\tau} = \frac{\sum E_w}{V}, \tag{7}$$

where E_W is total exergy of waste generating by the energy system; F and V are accordingly square and volume of the surrounding environment.

Environmental response on GTS load is determined by indexes of environmental change. They describe a change of chemical composition of environment by the difference of entropy per volume of the surrounding environment:

$$j_{V,\tau} = \frac{\Delta S}{V}, \tag{8}$$

where ΔS is a difference of the environment entropy by comparison with background value [34].

4. Integrated exergetic assessment of GTS

It is important to economically stimulate improved exergy efficiency and use of sustainable energy technologies. For these purposes exergy analysis can be applied together with economics. Depending on a level of task microeconomics or macroeconomics can be used. Exergetics and microeconomics form the basis of thermoeconomics [4, 6], which is also named exergoeconomics or exergomics.

The concept of utility is a central concept in macroeconomics. Utility is closely related to exergy. Within the scope of utilities, introduction of exergy taxes for use of fossil fuel and non-efficient energy technologies, developed in [9], is an example of the macroeconomic application of exergy concept.

In this paper principles of thermoeconomics are discussed for integrated exergetic assessment of GTS. Thermoeconomic method consists of exergy and economic analysis conducted at the component level of a GTS following exergy costing and evaluation of each GTS component. Using this method the following issues are chased: (i) identification of exergy destruction and losses; (ii) calculation of costs involved in exergy destruction and losses; (iii) calculation of product costs; (iv) optimisation of GTS in all life cycle stages starting from design stage for an energy system and following improvements under manufacture, exploitation, repair, renovation and utilisation stages; and (v) comparison of technical, economic and environmental alternatives and decision-making procedure concerning GTS management.

Many conclusions obtained by thermoeconomic method can be also received through different combined methods of energy and economic analysis. However, the advantage of thermoeconomics is that it replaced whole group of expensive methods by well-defined, systematic and united method of integrated assessment. In terms of modelling and computer simulations, it is an important issue.

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Let us examine interaction processes between GTS components. In Fig. 1 scheme of interaction processes in GTS is represented (arrows represent all type of mass, energy and information exchange between the GTS blocks: Production (1), Surface Waters (2), Groundwaters (3), Lithosphere (4) and Atmosphere (5): for example, arrow 1.4 means interaction process between Production and Litosphere; arrow GL means interaction process between Ground Waters and Litosphere; and m(A) means mass of waste formed by products entering in Atmosphere and so on). M_c and M_f are correspondingly mass of row materials and mass of final products in the Production block.

It is proposed to use integrated exergertic assessment of all processes of energy and mass transfer in atmosphere, surface waters, ground waters and litosphere. This assessment can be done for the life cycle of the GTS core – industrial object (Production in Fig. 1), because all exergy flows can be compared in the same energy units. Emission flows, which take place in the GTS life cycle, can be calculated and summarised. Therefore, on the stage of design of the GTS it is possible to make adequate scenarios of all emissions occurred in the GTS life cycle stages. This information can be used for ecological certification of the GTS core.

GTS, formed by a building, is another interesting example of the current challenge of how to make our built environment more sustainable (see, for example, [35]). In the UK urban regeneration of cities and towns is one of the urgent problems of sustainable development, because significant amount of old buildings nearly reach their life time and need in either renovation or utilisation. New expression of “sustainable demolition” has been introduced for a problem of old houses demolition and creating new eco-houses on the same place after its cleaning. It is proposed to use low-energy materials and recycle old houses materials where possible.

For these purposes, thermoeconomic method can be used in a range of tasks. For old houses it estimates exergy values of building materials, their possible recycling and costs involved. Exergy indicators and environmental indexes contribute to the environmental assessment of building areas. Decisions about redesign and replacement of components will be finally made.

Application of thermoeconomic method to new building concepts and sustainable construction GTS (i.e. eco-villages or eco-cities) results in significant savings in design and costs of system production. This is a great challenge to change current thinking about buildings as something, which is always in second place, to sustainable thinking about intelligent buildings with state-of-the-art design and technology.

Finally, thermoeconomics can help managers decide how to allocate research and development funds to improve sustainable building performance that noticeably contribute to building costs.

The future work will show whether exergy could be a united currency for all utilities supplied to a house. Perhaps in the future, a user will pay not for energy usage but for exergy usage, because different utilities can be compared only in exergy units. United bill will be generated in pounds for usage of exergy units. Yantovski proposed to consider such an approach and to use special units for exergy to distinguish energy and exergy flows, because they have the same dimension. He

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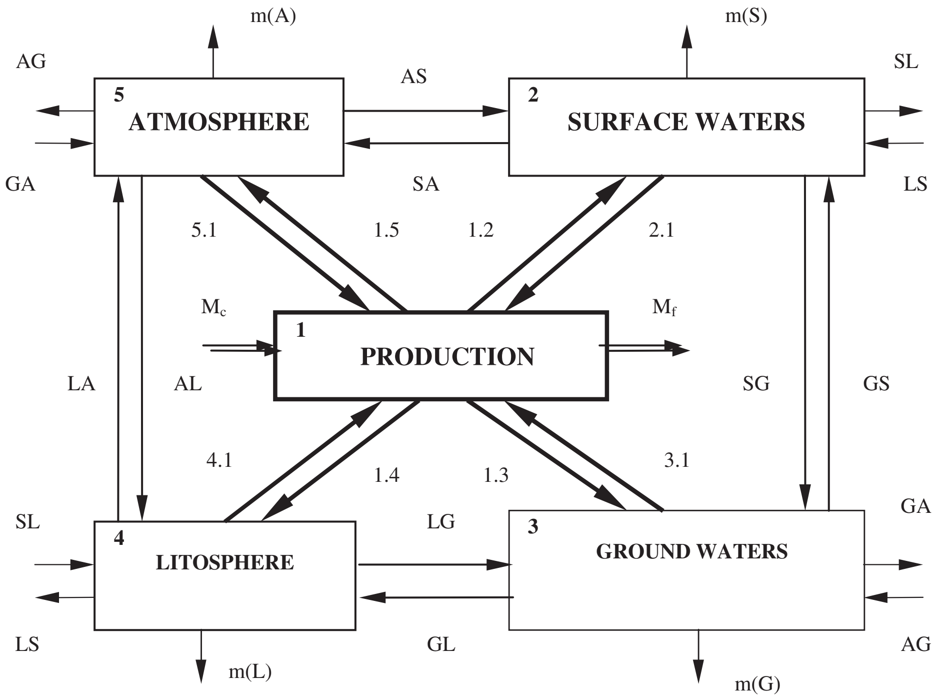

Figure 1. *Scheme of interaction processes in geotechnic system.*

offered to use 1 Gibbs as a unit for exergy in honour of J. W. Gibbs, who made one of the earliest contributions to the exergy concept in 1873 [10].

5. Conclusion

Thermodynamic indicators, based on exergy analysis, offer an opportunity to assess a geotechnic system and its energy technologies in terms of sustainability. Exergy is a well-defined concept, which provides a basis for integrated assessment of sustainability in a system. This assessment is performed by strict thermodynamic calculations and complex mathematical tools can be applied to optimise the system and to make system more environmentally friendly.

Integration of exergy and economic analysis provides a thermoeconomic method of sustainability assessment and improvement. Integrated exergetic assessment has the following advantages: (i) focusing on the nature of linkages between the system parts, its subsystems and elements comprising an integrated whole; (ii) identifying the functions of each component within that whole; (iii) assessment of each component environmental impact if any; (iv) investigating the dynamics of the system development and the conditions of its functioning in terms of sustainability; and (v) working towards sustainable development of the system on a basis for its subsequent

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optimisation. Complexity of exergy flow calculations is considered as a disadvantage of this method but the recent development of software and electronic databases of thermodynamic properties of substances allows a fast progress in this area.

Integrated exergetic assessment can help to close the gap between engineers and academics in understanding how to estimate system sustainability and to improve environmental quality. It is to be expected that in the future more practitioners will apply exergetic techniques to built environment systems.

Further work is underway to apply exergy indicators in case studies of sustainable buildings.

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