METHODS OF EVALUATION OF THE STATE AND EFFICIENCY OF THE URBAN ENVIRONMENT

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ABSTRACT:

Today, humanity is experiencing an "urban age", and therefore issues of good management of energy consumption and energy spent on utilization of waste in cities are becoming particularly acute. In this regard, the working group of the World Energy Council proposed a concept of the "energy balance" of the urban environment. This concept was that the energy produced should cover the energy consumed. Metabolism of the urban environment is so hot and so rarely studied by urban planners. This condition is linked first with the fact that metabolism is nothing more than a network of exchange of physical, energy resources and information. This is the real point of meeting the natural, technological, social, economic processes and their transformation into one another. Metabolism is the most important tool for knowing the real mechanics of the movement of resources in such a complex system as the urban environment. The content of the article is an analysis of significant energy and material flows characterizing the metabolism of the urban environment. We considered in the article a new energy paradigm. This paradigm will help in carrying out research in such areas as reducing the burden on the state of the environment, reducing environmental problems and reducing dependence on fossil fuels. Methods and models of metabolic processes in the urban environment will allow to implement in practice the concept of sustainable development of the urban environment, which is the development of the teaching V. Vernadsky about the noosphere.

1. INTRODUCTION

The EU's innovative policy is formed at the Pan-European, national and regional levels on the basis of a large number of strategies, programs and plans. A characteristic feature of the EU innovation policy is the variety of mechanisms for its implementation. In the list of the main strategic documents defining the pan-European policy, there is a new program "Strategy 20-20-20". This program is the successor of the Lisbon Strategy (European Commission Directorate).

The new energy strategy of the EU is dictated not only by the desire to reduce dependence on imported fuel, but also concern for the environment. The transition to alternative energy sources should radically improve the state of the environment in Europe. The EU has planned to reduce its greenhouse gas emissions by 20% up to 2020 and by 80 – 95% up to 2050. According to the EU directive, EU member states are obliged to take appropriate measures to ensure compliance with the environmental and environmental emission limits of enterprises and motor vehicles. In order to ensure further reduction of CO2 emissions by road, in 2011 the European Commission adopted the "Transport Strategy". According to this strategy, since 2050 in European cities there should be no motor vehicles with gasoline and diesel engines. In addition, 40% of jet fuel should be provided by alternative sources.

In the strategy they stressed the important role of energy in the urban environment (UE) and urban planning systems in general. That is, attention is focused on the need to plan sustainable energy development of the UE.

Urban environment is a no equilibrium system. The state of no equilibrium is determined by the scale of anthropogenic loads of the anthropogenic component of the urban environment on the atmosphere. Indicators of anthropogenic loads can be: population density, the area of built-up and impoverished territories, the weight of buildings and constructions, the volume of industrial production, the level of motorization, and so on (Bol'shakov, 2002; Karavaeva N.V., et al, 2011).

Summarizing the above, it should be noted that at the present stage of research, it is possible to assess the condition and effectiveness of the UE at a qualitative and quantitative level. Such an opportunity can be an assessment of the metabolism of energy flows in an urban environment. Complex modeling allows us to consider such a complex object as the urban environment in its entire integral integrity. Methodological approaches to studying the metabolism of UE have undergone a long evolutionary path. The analysis of literature (Bettencour L. A., 2007; Butera F., 2008; Research project, 2009; project conducted by the Economist Intelligence Unit – Munich: Siemens AG – 2009; Kennedy et al, 2007; Caputo P, 2010) shows that the last decade is characterized by increased interest in the field of research on the metabolism in the UE. In addition, the analysis makes it possible to distinguish between two interrelated and non-conflicting trends in the study of urban metabolism. The first direction describes the interaction between society and the environment in energy terms. At the same time, the second direction more widely describes the interaction on the basis of the use of solid streams (water, fuel, food, materials).

For the first time the concept of "metabolism" was proposed by K. Marx in his work "The main features of criticism of political economy" (1857 - 1858). The first concept of "metabolism" was introduced by biologists and physiologists in the 1830s. Then this concept began to be used by chemists and physicists. K. Marx assigned the concept of "metabolism"

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a central place in his understanding of the interaction between nature and society (Karavaeva N.V., 2011). As applied to the urban environment, the concept of metabolism was applied in (Bettencour L. A., 2007; Butera F., 2008; Research project, 2009; Kennedy et al, 2007; Caputo P, 2010) to develop a strategy for the sustainable development of cities and municipal communities. Urban metabolism can be defined as "the total amount of technological and socio-economic processes occurring in an urban environment and leading to increased energy production and lower costs for its consumption" (Kennedy et al, 2007).

A large number of modern works (Acebillo, 2008; Harvey D, 2011; Graham S., 2013; Newman, P., 2004) is devoted to questions of biophysical interaction between society and the environment. This approach is provided by taking into account the use of resources (energy, materials, land, etc.) and the results of their environmental impact, as well as on the socio-economic characteristics of the urban environment in general. The current concept of UE metabolism is based on an analogy with the metabolism of organisms. That is, we can draw the same analogy between the UE and the ecosystem (Patrakeev I. M., 2015). Cities like living organisms that consume resources from the environment and produce biomass and waste. The appearance of the metaphor "city as an organism" is associated with the evolutionism of Herbert Spencer (Tistol, 2013), who for the first time made an analogy between the urban planning system and the living organism.

The analysis of foreign experience shows the diversity of approaches to identifying the parameters of the urban environment that characterize its sustainable development (Bol'shakov, 2002; Karavaeva N.V., et al, 2011; Tistol, 2013; Patrakeev I. M., 2015). Ukrainian scientists cover problems in the area of assessing sustainable development of the environment both at the subnational level and in the context of the quality and safety of people's lives. In (Research project, 2009), some methodological approaches to the assessment of sustainable development of the city are generalized. At present, there are no generally identified methods, methodological approaches and technologies in assessing the effectiveness of the urban environment. This prevents the municipal structures from taking effective decisions on managing territorial development and implementing these decisions. The urban environment has large reserves to restore the energy balance. We must take into account such opportunities in new urban planning models based on the evaluation of metabolic processes. The purpose of the article is to generalize the concept of metabolism in the UE and to substantiate the methodology and principles of applying the claimed concept to such systems as the urban environment. Each urban environment is characterized by unique features and living conditions. Also in this article, we would like to analyze and identify the significant energy and material flows that characterize UE metabolism, and to provide their possible characteristics.

2. METHODS OF EVALUATION OF METABOLIC PROCESSES IN THE URBAN ENVIRONMENT

As was said above, the consumption of energy and the development of the city as an artificial environment is in close connection. Consumption of energy affects the processes of urbanization. This increases the anthropogenic load on the environment. As a result, the density of the population is increasing, the territory of cities and agglomerations is expanding, the density of urban areas is growing and their engineering infrastructure is saturated. And also the volume of industrial production is increasing, the level of motorization is growing. As a rule, this leads to an exacerbation of environmental problems in the UE.

Cities occupy not more than two percent of the earth's surface, but they use about 75% of the planet's total resources, in addition, more than 70% of the world's energy consumption falls on cities. World’s energy consumption is all energy from all energy resources consumed by mankind, in all industrial and service sectors of the economy in each country. Since global energy consumption is an energy measure of civilization, it is of paramount importance for the ecological and socio-economic spheres of life (Caputo P., 2010).

More than two thirds of the total energy consumption are needed to ensure global metabolism in the environment, which in turn generates more than two thirds of the global CO_2 emissions (Lozano S., 2008). Hence, cities are the most affected by the depletion of natural resources and climate change. So, according to the World Meteorological Organization (WMO), the amount of greenhouse gases is increasing at a record pace. In the new WMO Bulletin on Greenhouse Gas, it is noted that for a quarter of a century, the radiation exposure of these gases to the atmosphere has increased by a third. This gives rise to anxiety. The conclusions show that, for example, the concentration of CO_2 does not simply increase, it expands exponentially. Radiation effects of CO2 and other greenhouse gases (such as nitrous oxide (N2O), methane (CH4), as well as less common gases: sulfur hexafluoride, fluorocarbons and perfluorocarbons) increase annually the total radiation exposure by 34% since 1990.

American ecologist J. Odum called large cities "parasites of the biosphere". We consider this assessment to be fair, as cities consume a huge amount of oxygen, water and other resources. At the same time, these cities produce only carbon dioxide and pollution. On satellite images cities with their infrastructures resemble cancerous tumors (Graham S., 2013) (Figure 1). Such a sad scenario requires taking decisive measures to stop the consumption of fossil fuels in cities and optimize energy consumption in various spheres of life.

Taking into account the current state of the economy and technologies, it is necessary to develop a new energy paradigm, which will allow us to consider cities as part of a single ecosystem and move from a linear consumption process to a cyclical (i.e., processing and recovery). This is a new vector of development, the transition from the philosophy of megacities to the philosophy of "ecopolices". The new energy paradigm will create a modern efficiently operating UE, improve the efficiency of metabolic processes in the UE. This will reduce the burden on the environment, reduce environmental problems and reduce dependence on fossil fuels.

According to researchers, mankind is approaching the point where the extraction of fossil fuels will reach its maximum due to depletion of natural resources. This will have the most unpredictable consequences for climate change and "food security". It is worth noting that by 2100, minerals should not be used as fuel if the world wants to avoid the dangerous consequences of global climate change. This is the central point of the report of the Intergovernmental Panel on Climate Change (IPCC). A brief overview of this report is presented in

Copenhagen, as a result of intensive week-long debates of scientists and statesmen (Lozano S, 2008).

It is noted that the main indicators of UE metabolism are interrelated. As a result, a feedback effect occurs. For example, recent studies show that an increase in gross domestic product by 1% leads to an almost equivalent increase in energy consumption, while an increase in population by 1% leads to an increase in energy consumption by 2.2% (Research project, 2009).

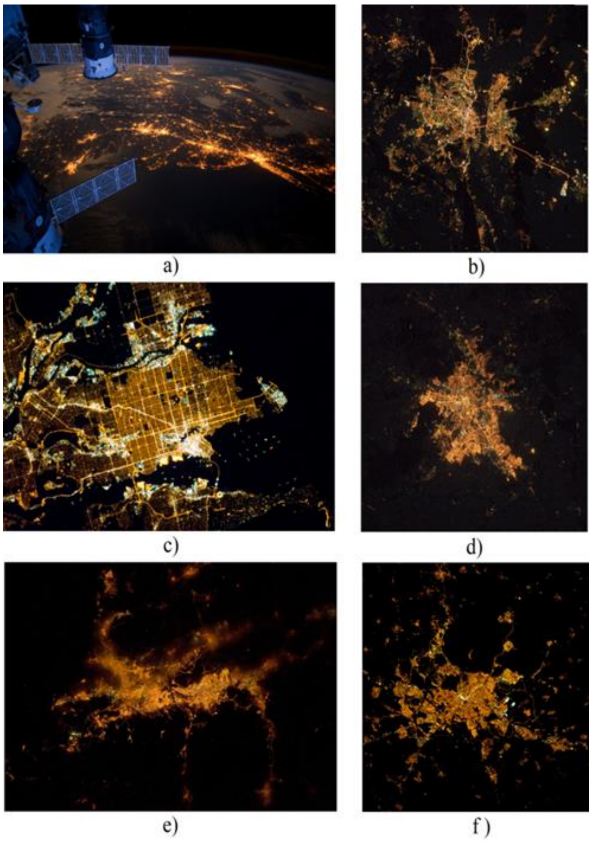

Figure 1. Pictures of cities at night made from a height of 300 km:
a) cities along the Atlantic coast of the United States,
b) the ancient city of Kyiv, c) night Kharkiv, d) the city of Madrid,
e) the city of Vancouver, f) night of Bilbao
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Energy is one of the most important integrating concepts that allows us to explore the relationship between the ecosystem and the socio-economic system of the UE. For example, in (Butera F, 2008), energy is defined as the useful energy used directly or indirectly for the creation of the final product or for the provision of services. Useful energy allows us to evaluate the processes occurring in the UE in the production of products and services. Moreover, the estimation of this energy can serve as a common metric of ecological and produced social and economic values. In general, energy can be used as a general basis for studying material-energy flows in socio-economic systems (Urban adaptation to climate change in Europe, 2016).

Support for the life of the UE, the cycle of substances, that is, the very existence of the UE depends on a constant inflow of energy. This energy is necessary both for the organism and for the production of products and services. Substances continuously circulate in various subsystems of the urban environment. These substances can be reused. Meanwhile, energy can only be used once. That is, there is a linear flow of energy through the urban environment.

One-way flow of energy, as a universal phenomenon of nature, occurs as a result of the laws of thermodynamics. The first law of thermodynamics (the law of conservation of energy) asserts that energy can be transformed from one form (for example, light) into another (for example, the potential energy of food). Thus energy can not disappear and can not appear from anything.

The second law of thermodynamics states that there can be no process associated with the transformation of energy, without the loss of a part of it. A certain amount of energy in such transformations is dissipated as inaccessible heat energy, and consequently, irretrievably lost. The analysis of energy flows in the UE is based on the principle of the maximum flow of Alfred Lotka. A. Lotk's hypothesis is that "... the direction of evolution is such that the total energy flow passing through the system reaches the maximum value that is possible for a given system". In modern publications (Acebillo J., 2008; Graham S., 2013; Harvey D., 2011; Newman P, 2004) it is shown that this hypothesis leads to the following treatment. Systems that make the best use of energy flows for existence and development (other things being equal) will gradually increase their numbers. This in turn will lead to an increase in the flow of energy through this system.

An interesting approach in using the concept of urban metabolism was demonstrated by university students in Toronto (Codoban & Kennedy, 2008) (Figure 2). Here they used the unit of analysis "metabolism of the urban quarter". In the opinion of most scientists, the application of the metabolic approach (for example, the study of moving the material flows) for urban planning should today become a common practice, rather than a single experiment.

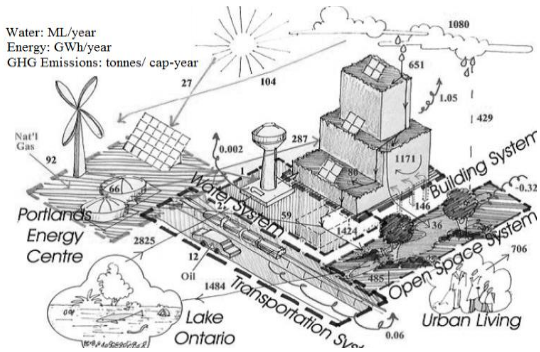


Figure 2. Presentation of the sustainable metabolism of the Toronto city area (Codoban & Kennedy, 2008)

The city consumes energy resources in the form of fossil fuels, food and water. The city uses information resources and attracts new residents to this process. Thus, the city ensures the development of production and services. The result of the functioning of the UE is reflected not only in the production of material resources and new information. The UE also produces a significant amount of solid, liquid and gaseous waste. These waste pollute the natural environment, have a negative impact, they change the climate and landscape. The urban environment is usually viewed as an open non-equilibrium system. This system is characterized by a high degree of internal organization.

A high degree of internal organization is characterized by complex schemes of human activity. These schemes are implemented within the urban area; they are characterized by a complex morphology of urban space. This point of view allows us to apply the basic theses of thermodynamics for studying the functioning of the urban environment as a no equilibrium system.

Entropy and free energy are two basic concepts of thermodynamics and can be used to understand metabolic processes in an urban environment. The first law of thermodynamics states that the internal energy of the system together with its environment remains constant. This is one of the wording of the law of conservation of energy. Such a formula shows that the internal energy of the system is not lost and will not be obtained under any system changes. In the system, energy can only be transformed from one form to another.

The second law of thermodynamics states that the entropy of the system under unmanaged processes increases. In thermodynamics, by entropy is meant a measure of the disorder and chaos of the system. The entropy of the system reaches its maximum when the system comes to equilibrium. In our case, entropy is a measure of the orderliness of the system, depending on the information content. The more internal organization of the system is higher (the more ordered structure of the system), the less is its entropy. Free energy is that part of the change of the internal energy of the system, which can turn into a work, in other words, it is "useful energy". Free energy is defined as (Acebillo, J., et al., 2012):

$$G = U - T{\cdot}S \tag{1}$$

where U = internal energy of the system
T = temperature of the system
S = the entropy of the system.

Free energy has clear and clear meaning in terms of energy, it can perform a useful work. In this sense, free energy can be interpreted as the energy of the potential of the urban environment. The change in entropy ΔS of a system is usually written in terms of thermodynamics as the sum of two componentsc (Acebillo, J., et al., 2012):

$$\Delta S = \Delta_{ext} S + \Delta_{int} S \tag{2}$$

where

ΔS_{ext} = the change in the entropy of the urban environment as a result of the exchange of energy and matter with the environment

ΔS_{int} = a change in the entropy of the system

ΔS_{int} = is associated with irreversible internal processes that tend to break the order in the organization of the system.

In a more general form, the second law of thermodynamics determines that the internal entropy of a system is always positive:

$$\Delta_{int} S \geq 0 \tag{3}$$

Physical, chemical and biological processes that lead to an increase in entropy are commonly referred to as dissipative processes. A high level of internal organization (correspondingly, a low level of entropy) can be maintained in the system only if the entropy that is generated by internal irreversible processes is reduced based on the constant use of certain mechanisms and technologies. The external component associated with the exchange of material and energy flows between the UE and the environment can be written as:

$$\Delta G_{ext} = \Delta U_{ext} + \Delta S_{ext} \tag{4}$$

At the same time, the second component associated with internal processes in the UE is simply proportional to the entropy produced:

$$\Delta G_{int} = -\,\mathrm{T}{\cdot}\Delta S_{int} \tag{5}$$

That is, the internal production of energy is zero, since the first law of thermodynamics asserts that energy does not appear and does not disappear, but only passes from one state to another.

From the second law of thermodynamics it follows that internal processes tend to irreversibly dissipate free energy:

$$\Delta S_{int} \geq 0 \rightarrow \Delta G_{int} \leq 0 \tag{6}$$

The division into entropy and free energy for both internal and external processes in the system makes it possible to understand the relationship between the support of a high level of organization in any system and its degradation. The system should constantly replenish, import free energy from the environment. Thermodynamic methods are useful and, moreover, are important for the analysis of energy transformations, understanding of the processes of self-organization and violation of order in such complex systems as the UE.

For this reason, a complex system can function only by consuming free energy (that is, natural resources), receiving them from the environment and interacting with them. In addition, only open systems (systems that intensively exchange material and energy flows with the environment) can constantly maintain their order, have the opportunity to self-organize only if there is a continuous supply of free energy from the environment (Bettencour L. et al, 2007; Karavaeva N.V. et al, 2011).

There is a metabolic point of view on the functioning of the urban environment today, but it still not commonly accepted. In general, metabolism is a combination of chemical processes in biological organisms that occurring in all living organisms and provide the production of both energy and other substances necessary to support life. Urban environment like an any biological system is characterized by material and energy flows that provide and support all the essential processes which are necessary to maintain the city's viability. Urban environment like biological systems emits material and energy streams in the form of waste of life, rubbish and heat.

Thermodynamic and metabolic points of view are closely interrelated, because the metabolic system is a typical example of a no equilibrium thermodynamic system.

Metabolic and ecological systems can be represented as chemical machines that carry out some useful work. The result of that work is transformation of material and energy flows from the environment into other types and forms of energy and substances. The energy and substances of other types and forms enter into the environment in the form of waste as a result of such activity. The useful work spent in the system is aimed at supporting the complex organization and functioning of the system, increasing its biomass.

In accordance with the first law of thermodynamics, the amount of free energy ΔG exchanged by the system with the environment is equal to the amount of energy ΔE, which is scattered in irreversible processes and spent for the performance of the work A:

$$\Delta G = \Delta E + A \tag{7}$$

The efficiency η of such a chemical transformation is defined as the ratio of the accomplished work A to the free energy ΔG, that used to exchange between system and environment (Bol'shakov B. E., 2002):

$$\eta = \frac{\mathrm{A}}{\Delta \mathrm{G}} = \frac{\Delta \mathrm{G} - \Delta E}{\Delta \mathrm{G}} = 1 - \frac{\Delta E}{\Delta \mathrm{G}} \tag{8}$$

Expression (8) shows that the system that minimizes the degree of energy dissipation ($\Delta E \rightarrow 0$) or the degree of entropy production ($\Delta S \rightarrow 0$) will be effective.

Thus, the mathematical expression (8) demonstrates the principle of the minimum of entropy production, from which it follows that the process of self-organization can occur only in open systems by the exchange of energy and matter with the environment, which in turn ensures the minimization of entropy production. Efficiency will increase if the system increases the amount of work done on the amount of free energy received.

The studies carried out have shown that many cities in Europe are different in efficiency degree in metabolism case. The classification of cities in Europe was performed according to 22 parameters (from population density to possible life expectancy) in order to understand the level of effectiveness of their functioning (Figure 3) (Acebillo, J., et al., 2012). Figure 3 shows that the level of effectiveness of cities functioning is the biggest in Stockholm and Oslo, the smallest is in Budapest and Bucharest. But it is important to find out why one city is more efficient, and the other is less and how it can be changed, because the consequences of bad metabolism of the ur environment are low quality of life of the citizens, high cost of transport, and so on.

In Ukraine, when studying the urban environment, it is necessary to solve the problems connected with the definition and measurement of quantitative indicators of metabolism in heterogeneous subsystems that create the urban environment, including ecological, socio-economic and other. Thus, the improvement of tools for modeling metabolic processes in the urban environment is an important task in the direction of development of planning strategies for town-planning systems. On the basis of the developed software tools on the example of the city of Poltava, an assessment of the quality of the urban environment has been performed on individual cadastral districts, based on 32 input indicators covering transport, city-building and social-economic subsystems of the city. Separate indicators of the urban environment of the city of Poltava are shown in Figures 4 (a), b), c), d)). Geoinformation technologies, in particular ArcGIS 10, were used to assess the state of the urban environment. The program for evaluating the effectiveness of the urban environment was implemented in the MatLab-2009 environment. The proposed indicator for the assessment of the efficiency of the urban environment allows linking many different aspects of the city system to obtain an assessment of the city's efficiency. Figures 6, 7 shows the dependence of the indicator of the efficiency of the urban environment in the cadastral zone of 10 (Figure 5) Poltava city from the amount of energy consumed for buildings heating. These graphs show that the sensitivity of assessing the effectiveness of the urban environment is different, depending on the changes in the variables studied.

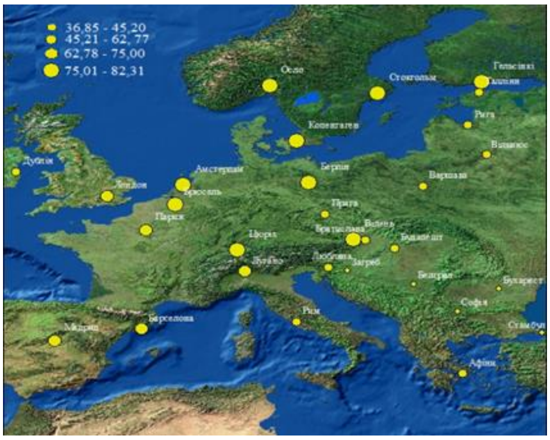


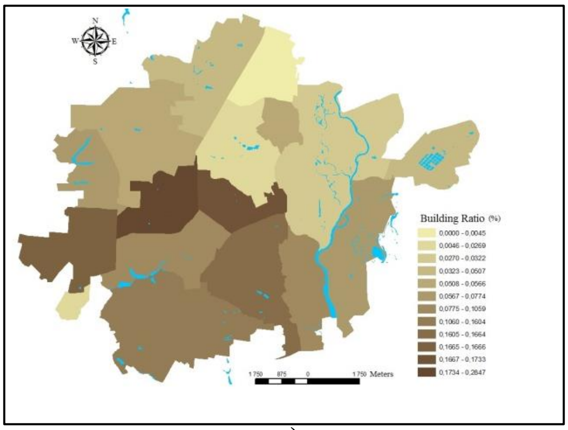
Figure 3. Estimation of efficiency of metabolic processes of cities in Europe (Acebillo, J., et al., 2012)

For example, the reduction on 0.1 kg/inh·y of solid household waste generated by population in a dense urban development of provides an increase of urban environmental efficiency by 5%, while a decrease in the amount of energy consumed for the heating of buildings and structures by 10 kWh/m2 provides an increase in the efficiency of the urban environment by 8-10%. In fig. 8 shows the surface of efficiency, depending on the amount of energy consumed for the heating of buildings and produced solid household waste, which can be interpreted as a kind of landscape of the urban environment of the cadastral zone 10 of Poltava.

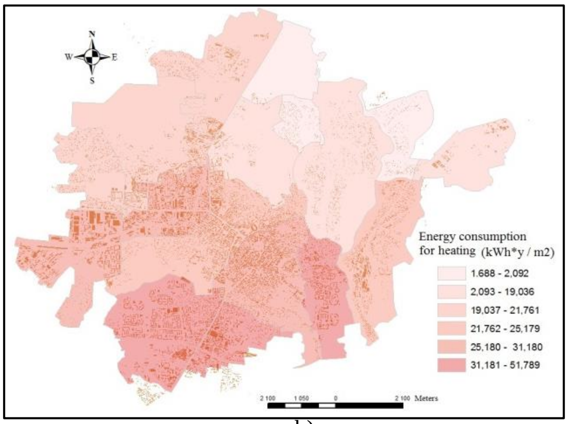
3. CONCLUSIONS

Analyzing the foregoing, one can state that the analysis of matter-energy flows, the study of the processes of transformation of matter-energy flows is a very important aspect in assessing the metabolism in the urban environment. The today notion of the metabolism of the urban environment is widely used in scientific literature, but not yet sufficiently investigated. The development of models of metabolism in the urban environment will raise the productivity of resource use, increase the presence of nature in the city's living space, create cities with a "closed metabolic cycle", waste of which does not overburden and does not destroy the environment.

Methods and models of urban metabolism may have practical implications for the control of the use of such resources as water, energy, materials and products, and to ensure comparability of resource efficiency in different cities in order to ensure their sustainable development. Promising methods and models of urban metabolism will provide solutions to the challenges of improving the management of natural resources: to determine which social and environmental resources are close to depletion, how to slow down their consumption, or to use other strategies for substituting resources.



a)



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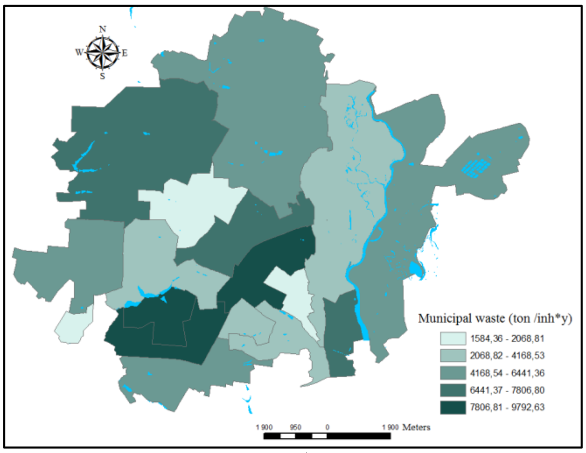

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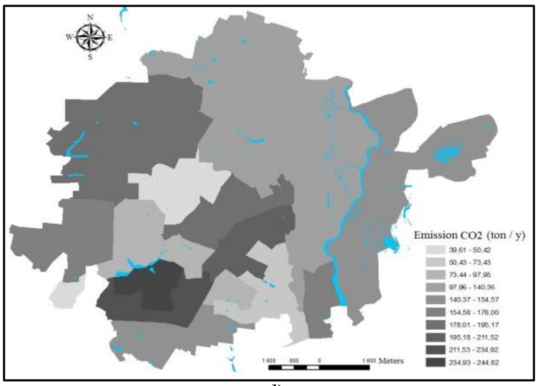

d)

Figure 4. Geoinformation modelling the state of the urban environment indicators: a) building ratio (%), b) energy consumption for hearting (kWh·y / m^2), c) municipal waste (ton / inh·y), d) emission CO_2 (ton / inh·y)

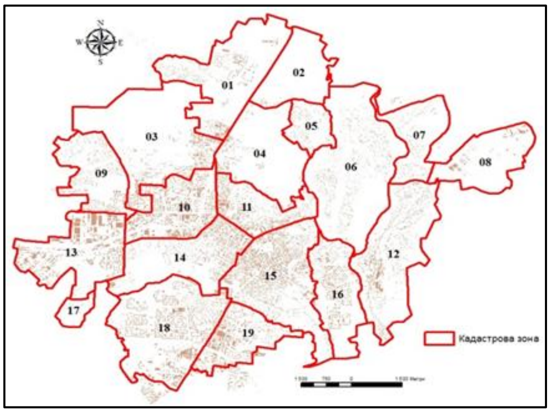

Figure 5. The numbers of the cadastral zones of Poltava city

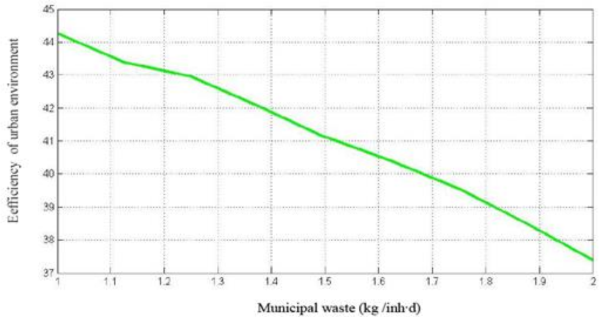

Figure 6. Dependence of the indicator of the efficiency of the urban environment in the cadastral zone of 10 m. Poltava city from the amount solid household waste

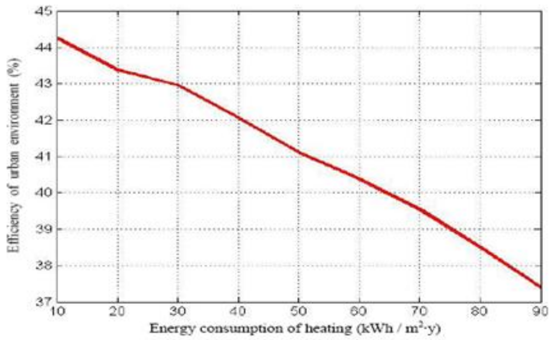

Figure 7. Dependence of the indicator of the efficiency of the urban environment in the cadastral zone of 10 m. Poltava city from the amount of energy consumed for buildings heating

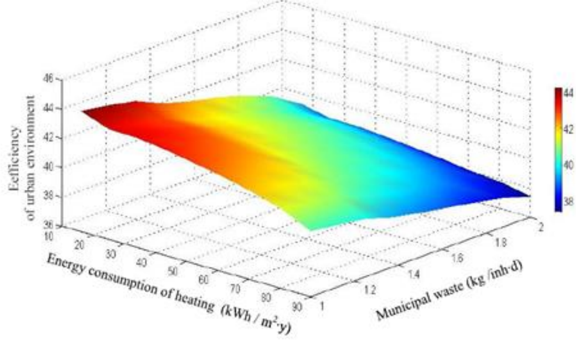

Figure 8. The surface of the efficiency of the urban environment in the cadastral zone of 10 m in Poltava city, depending on the amount of energy consumed for the heating of buildings and produced solid household waste

All main subsystems of the urban environment harmoniously interact and develop only in conditions where the flows of energy, substance and information are within the appropriate limits, and are favorable to man and the environment. At present, when attempts are being made to model and predict the sustainable development of such a complicated system as urban environment, the use of quantitative methods used during the last decade allowed only partial results to be obtained, because the mechanisms that lead to the development and improvement of the urban environment are extremely complex. In such conditions, an interdisciplinary approach is important that will overcome the difficulties associated with modeling various aspects of the functioning of the urban environment and provide computational transparency and efficiency of the modeling process, as well as realize the concept of sustainable urban environment, which is the development of the doctrine of V.I. Vernadsky about the noosphere.

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