*Bulgarian Chemical Communications, Volume 56, Issue 4 (pp. 433-440) 2024 DOI: 10.34049/bcc.56.4.5679*

# The application of an energy metric (EROI) for the analysis of a city energy profile

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Received: November 09, 2024; Revised: November 20, 2024

Energy return on investment (EROI) is an energy metric used to build models comparing different energy extraction, transport, and use options. Its demand to date is determined by two limitations: the development of correct calculation and forecasting methods, as well as establishing the limits of practical applicability. This article proposes a solution to the second limitation, namely, the calculation of the weighted average EROI of a city's electrical energy consumption system. This value can be useful in the analysis of the fuel and energy balance, economic development potential, and sustainability of a city energy system. The authors calculated the balance of the energy system based on the volume of electrical energy consumption for 4 megacities of the world: Toronto-Hamilton-Oshawa, New York, London, and Moscow, indicating the estimated weighted average EROI based on the world average values of each energy resource. A comparison of the weighted average EROI of London and Moscow calculated using global and local values is presented. The results show that EROI for local energy resources allows for a more reliable calculation for individual cities.

**Keywords:** EROI, urban planning, urban energy system, energy consumption, energy conservation, urban metabolism.

## INTRODUCTION

There are about 20 cities in the world with a population of over 10 million people. Moreover, this value is typically used to designate a city not as a set of historically developed areas, but as a modern urban agglomeration consisting of several settlements. Examples of such agglomerations are Toronto - Hamilton - Oshawa or Tokyo - Yokohama. Electrical energy consumption by the world's megacities accounts for approximately 10% of global consumption. In turn, modern trends towards energy saving and carbon neutrality are in clear contradiction with the positive dynamics of energy consumption growth that have been established over the past decades. Of research interest is the question of the practical applicability of an indicator such as EROI for analyzing a city's supply of energy resources. This article analyzes certain aspects of the energy structure of the world's megacities with the prospect of obtaining an answer to the above question.

## APPLICATION OF EROI AS AN ENERGY, ECONOMIC AND SOCIAL INDICATOR

The structure of power generation in megacities is extremely diverse, especially taking into account the fact that electricity can be transmitted over tens or hundreds of kilometers, and power plants are located outside the cities and regions in question. It is customary to highlight EROI as one of the indicators of energy resource efficiency: energy return on investment - the ratio of energy received to energy expended or energy profitability [1, 2]. This indicator is often used when constructing economic models to compare different options for energy production, transport and use [3, 4], as well as to select a priority energy transition model [5].

Article [6] is devoted to a review of economic assessments of oil and gas resources, including EROI. The authors note the appeal of using EROI compared to traditional methods of economic assessment: net present value, differential rent due to its comprehensiveness and consideration of an expanded range of costs: energy production, transport, environmental safety, energy efficiency. In addition to analyzing methodological approaches, the article presents statistical data on a number of energy carriers, for example, EROI of shale oil in the United States in the period from 2010 to 2015.

EROI is often used to analyze the prospects for the use of renewable energy sources (RES). In particular, in [7] this indicator is considered as one of the barriers to the development of renewable energy sources, along with a shortage of fresh water, rare earth metals and the intermittent nature of generation. In [8], along with the energy and economic applicability of EROI, the authors note its social significance. It is noted that EROI = 12 is the

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minimum for the existence of a society, conversely an EROI = 5 is associated to a possibility of famine.

A similar analysis is presented in works [9, 10], which establish a connection between EROI and the human development index, along with other social indicators. Noting the correlation between these indicators, the authors emphasize the need to increase the availability of energy resources with a high EROI in developing countries [9]. Table 1 shows the minimum EROI value for the existence of various types of activities according to [8].

In [11], EROI is considered as a dynamic indicator of the profitability of an energy source. It is shown that the EROI of oil and gas in the US decreased markedly over the 100 years spanning the period between 1910 - 2010 from 1200 to just 10, with that trough having already been reached in the 1960s. Moreover, it has shown extremely weak negative dynamics since then. In Canada the EROI of oil and gas was 16 in 2005. It is important to note that the EROI of oil and gas is typically calculated jointly, since oil and gas fields are often coupled.

**Table 1.** Minimum EROI value for the existence of various types of activities

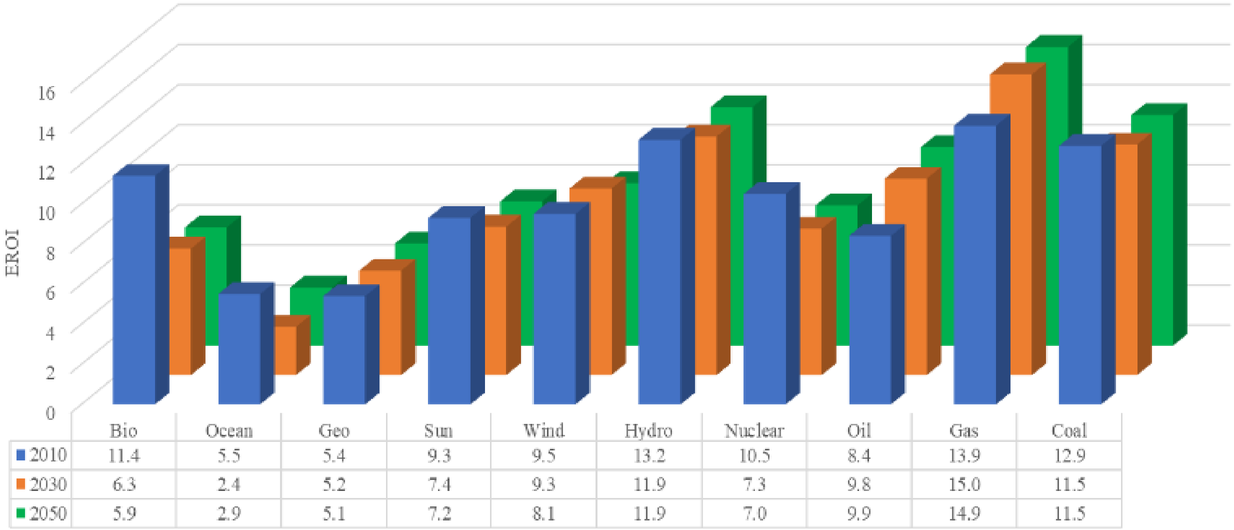
| Activity | Minimum EROI |
|---|---|
| Art | 14 |
| Medicine | 12 |
| Education | 9 – 10 |
| Family support | 8 – 9 |
| Healthy eating | 5 |
| Transport | 3 |
| Energy recycling | 1.2 |
| Energy generation | 1.1 |

In [12] the dynamics of oil and gas EROI are also analyzed on average both worldwide and for some individual countries: USA, Canada, China, Mexico, Norway. It is shown that the world average for the period from 1990 to 2010 decreased from 32 to 20. For individual countries, the EROI of oil and gas is respectively: USA - 12 (2007), Canada - 15 (2010), China - 10 (2010). Mexico – 45 (2009), Norway – 21 (2008).

In [13] EROI values are given for all energy resources used in the UK: 3.6 – coal, 1.7 – oil, 14 – natural gas, 30 – nuclear energy, 1.1 – biomass, 58 – hydropower, 18 – wind energy, 3.3 – 8.6 – solar energy. The average EROI for all types of energy carriers in the UK is 9.0 [14]. The papers [15, 16] present data on EROI for gas in China produced from various sources: oil and gas fields, shale gas, etc. The indicator, as a rule, varies from 10 to 13, with the exception of synthetic gas from coal, for which the EROI is 5. Similar data for China can be found in [17]: 10.0 – oil and gas, 25 – coal. For Russian natural gas, EROI is 74 according to data for 2016 [18]. At the same time, this value has been in the 70-83 range for 12 years.

Article [19] is an extensive study devoted to methodological approaches for assessing EROI for renewable energy sources. Researchers consider 3 global scenarios for the energy transition by 2060 with a share of renewable energy sources equal to 50, 75 and 100%, respectively. It is predicted that for the first scenario the integral world EROI in 2060 will be 10, and for the second and third scenarios - 6 and 3 – 5 respectively. It is rightly noted that scenarios 2 and 3 will lead to a decrease in EROI below the threshold values (EROI = 10 – 15) necessary for the functioning of modern industrial society. An additional factor limiting the development of renewable energy sources is the excess of the required volume of valuable metals in relation to the known one. In particular, for Scenario 3 (100% renewable energy sources by 2060), the estimated total mining demand will exceed current reserve levels for tellurium, indium, tin, silver and gallium. When planning an energy transition, it is usually assumed that the only significant constraints are political and economic (i.e., government political will and monetary investment). However, the results presented in [19] show that the EROI of the power system is also an important factor that should be taken into account when assessing the rate of implementation of renewable energy sources.

There are a number of publications devoted to a specific energy carrier. In particular, in [20] the EROI of solar energy is calculated for Swiss conditions. Depending on the calculation method, this indicator varies from 7 to 10, which, according to the authors, is a decent result for the energy carrier in question. However, the weak point of such studies is often the neglect of the need for energy storage, especially given the significant contribution grid-tied storage makes a to the EROI for renewable energy sources. At the same time, there are works in which the optimal storage capacity is calculated based on the problem of maximizing the "solar power plant – electrochemical storage" energy unit. In [21] it is shown that a correctly selected storage device can increase the EROI of a power plant using renewable energy sources by 1.5 – 2.0 times, although, as a rule, the need to introduce network storage devices reduces the technical and economic indicators of such installations [22].



| | Bio | Ocean | Geo | Sun | Wind | Hydro | Nuclear | Oil | Gas | Coal |
|---|---|---|---|---|---|---|---|---|---|---|
| 🟦 2010 | 11.4 | 5.5 | 5.4 | 9.3 | 9.5 | 13.2 | 10.5 | 8.4 | 13.9 | 12.9 |
| 🟧 2030 | 6.3 | 2.4 | 5.2 | 7.4 | 9.3 | 11.9 | 7.3 | 9.8 | 15.0 | 11.5 |
| 🟩 2050 | 5.9 | 2.9 | 5.1 | 7.2 | 8.1 | 11.9 | 7.0 | 9.9 | 14.9 | 11.5 |

**Fig. 1.** Forecast of global average EROI for various types of energy resources until 2050

In [23] a forecast of the global average EROI for various types of energy resources until 2050 is presented.

The authors consider several scenarios for the energy transition with different shares of renewable energy sources in the future. Fig. 1 shows data only for the base scenario.

Based on the review, it becomes obvious that there are several different methods for calculating EROI, which take into account different amounts of energy costs for obtaining, transporting the energy resource and waste disposal during its use. For example, the wide spread of EROI for nuclear energy (from 5 to 75) is due to both the availability of the initial resource for an individual country and the cost of processing or disposal of waste.

## EROI OF A CITY ENERGY SYSTEM

As a practical application of EROI, it is proposed to use the following criterion: the weighted average EROI of the given city's electrical energy consumption system:

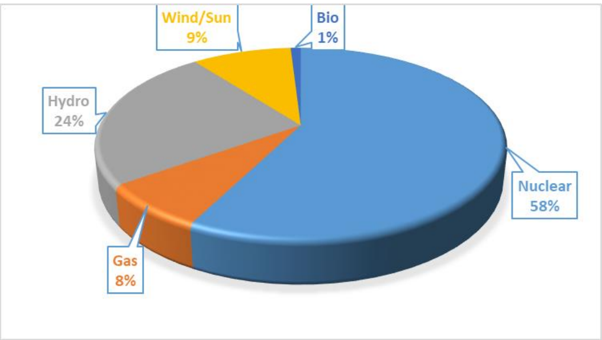
$$EROI_{city} = \frac{\sum_{i=1}^{n} W_i \cdot EROI_i}{W_{sum}}$$

where: $EROI_{city}$ is the weighted average EROI of the city's electrical energy consumption system; $EROI_i$ is the EROI value of the i-th energy resource used to generate electrical energy for the needs of the city; $W_i$ is the volume of electricity consumption in the city using the i-th energy resource; $W_{sum}$ is the total volume of electricity consumption in the city.

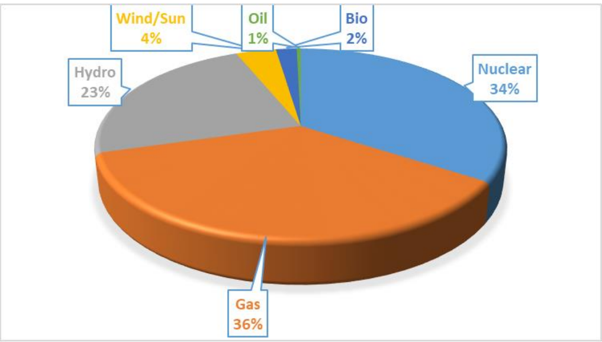
It is important to note that from a practical point of view, to obtain a snapshot for the reporting period (month, quarter, year), it is necessary to use the actual electricity production from various sources / the volume of electricity consumption by the city, and not the installed capacity of a power plant. In that case, it is possible to track the seasonality factor and the influence of the load factor on the city's energy balance. For example, power plants using renewable energy sources (solar, wind) often have a load factor several times lower than that of power plants using fossil fuels. Then their share in the city's energy balance in terms of installed capacity can reach 10–20%, and in terms of output – 3–5%, which results in increased accuracy through adjustments to the calculation of the weighted average EROI of the city's electrical energy consumption system.

Fig. 2 shows the balance of the energy system based on the volume of electrical energy consumption for 4 megacities of the world: Toronto-Hamilton-Oshawa, New York, London, Moscow, indicating the estimated weighted average EROI based on the world average values of each energy resource [23]. For Moscow, natural gas is accepted as the only type of fuel, for the other cities - data from official government sources is used: Toronto-Hamilton-Oshawa [24], New York [25], London [26].

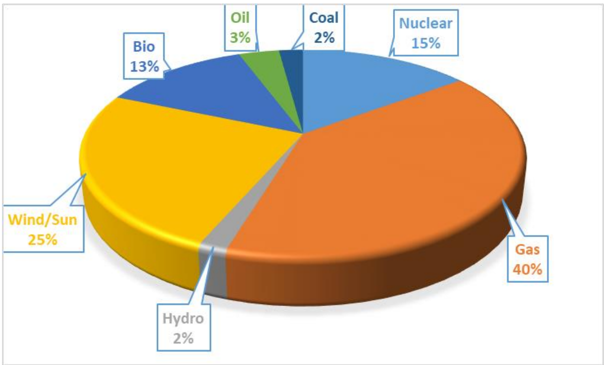
Based on the data presented in Fig. 2 we can conclude that the weighted average EROI of the world's megacities under consideration is approximately the same ranging between 11 - 14 and weakly depends on the structure of electrical energy consumption. However, this logic is sound only if we operate with the world average EROI of energy resources according to [23,31,32]. When working with EROI for local (national) energy resources, the situation is in sharp contrast.



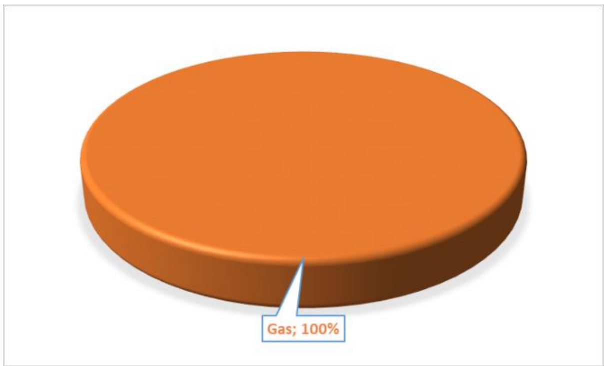
a) Toronto-Hamilton-Oshawa, $EROI_{city}$=11.3



b) New York, $EROI_{city}$=12.3



c) London, $EROI_{city}$=11.7



d) Moscow, $EROI_{city}$=13.9

**Fig. 2.** Balance of urban electricity consumption and weighted average EROI

Figure 3 shows a comparison of the weighted average EROI of London and Moscow calculated using global averages [23] and local values, respectively [13, 18].

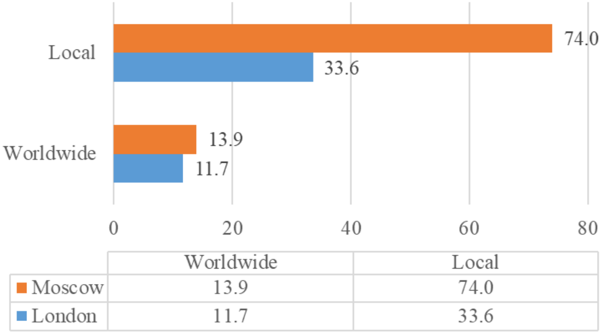


**Fig. 3.** Weighted average EROI of the electrical energy consumption system of Moscow and London calculated using global average and local values

From Fig. 3 it follows that EROI for local energy resources allows for a more reliable calculation for individual cities, obtaining results that are several times higher than the results when calculating using world average values. It is important to note that for both London and Moscow, the weighted average EROI is multiple times higher than the threshold values (EROI = 10 – 15) necessary for the functioning of a modern industrial society.

Another significant result that can be obtained by analyzing global average data through tracking the projected dynamics of the EROI for the period up to 2050. The data presented in [23] indicate that EROI for renewable energy sources have negative dynamics in the future 2050, and the EROI of oil and gas – positive. Obviously, this factor will lead to an additional reduction in the weighted average EROI of the electrical energy consumption system of a city or state when implementing “green” energy transition measures.

## ANALYSIS OF MEGACITIES ENERGY TRENDS

The electronic resource Metabolism of Cities [27] has an extensive database of statistics on the consumption of fuel and energy resources by cities over the past 20–25 years, indicating the source of information (usually scientific publications in international ranking journals). Figs. 4 – 7 present data on the dynamics of energy consumption, water and the volume of waste disposal in the largest cities of the world, built on the basis of the Metabolism of Cities resource.

The presented figures demonstrate that in the first decade of the twenty first century there was a significant (in some cases two- and three-fold increase) consumption of energy and fresh water by the world's megacities. The task of adequately comparing the climate (energy and ecological) efficiency of large megacities remains not only significantly relevant, on the contrary, the reckless use of conventionally calculated indicators of greenhouse gas emissions (without taking into account the main abundant greenhouse gas - steam) in the mythical coverage areas of large agglomerations does not provide a sufficient understanding of the essence of what is happening in cities., Gaining an insight into the real energy-ecological efficiency of the urban metabolism, would aid the development of effective measures to increase efficiency.

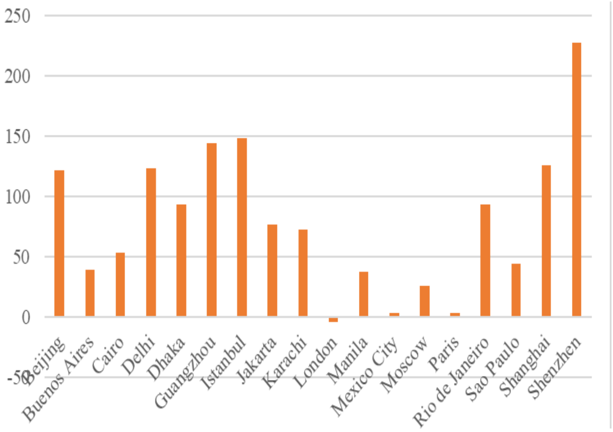


**Fig. 4.** Dynamics of energy consumption by stationary sources, % 2001 – 2011

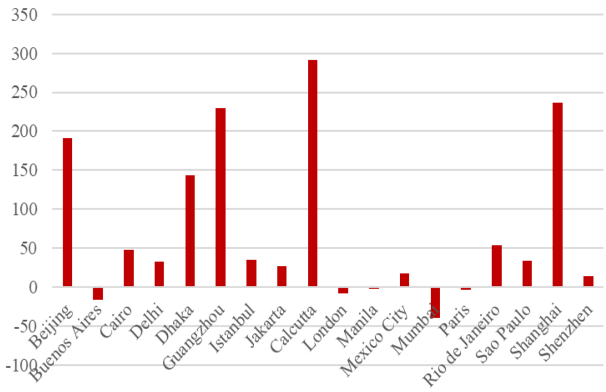


**Fig. 5.** Dynamics of energy consumption by transport, % 2001 – 2011

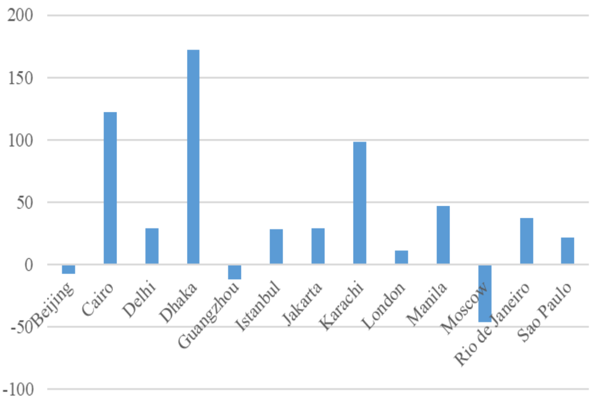


**Fig. 6.** Dynamics of water consumption, % 2001 – 2011

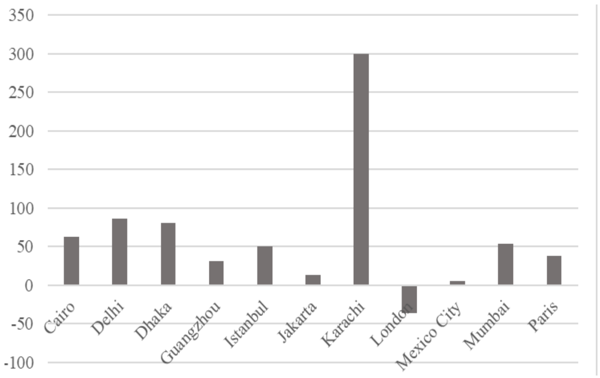


**Fig. 7.** Dynamics of waste disposal, % 2001 – 2011

Global challenges to environmental safety include the impacts of climate change on the planet, the increased consumption of natural resources amidst declining reserves, the loss of biodiversity and more. Among the mechanisms for implementing state policy in this area is the creation of an environmental audit system, informing the population and organizations about dangerous hydrometeorological and geophysical phenomena, the environmental state, and the introduction of comprehensive environmental permits for environmentally hazardous industries using the best available technologies.

Fig. 8 shows the results of calculating the specific consumption of electric energy from a city's population. For easier interpretation of the graphical information, only cities with an annual electricity consumption exceeding 5000 kWh/person are labelled on the scatter plot.

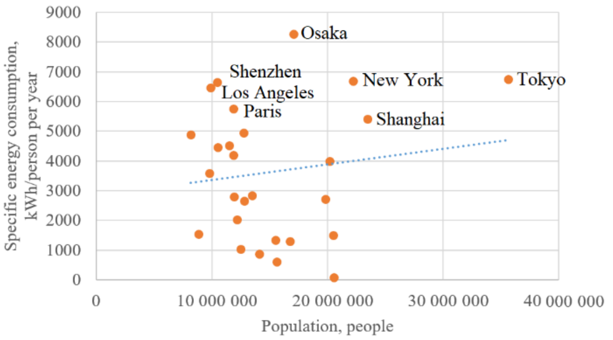


**Fig. 8.** Electricity specific consumption of population (kWh/person/year)

The trend line (marked in blue) shows a weak growth dynamics of the indicator as a function of population, which may signify that the energy limit under the modern structure of electric energy consumption by the city is about 7000 kWh/person per year. Further population growth of the city to 15, 20 or 30 million people represents a repetition of existing practices of energy production and consumption, adjusted for regional and climatic features. For instance, for Moscow this figure is only 4516 kWh/person per year.

Fig. 9 shows the dependence of the density of electric energy consumption on the density of the population. In this calculation, the population density was calculated not per square kilometer of urban territory, but per square kilometer of urbanized territory within the city.

Despite some dispersion of values due to the different social and economic specifics of the megacities of the world, in Fig. 9 one can observe an established trend of growth in the density of electric energy consumption, which is about 30 GWh/km$^2$ with an increase in population density by 10 thousand people/km$^2$. Thus, an increase in the density of living per person increases electricity consumption by an average of 3,000 kWh/person per year. By analogy with Fig. 8, Fig. 9 shows only the largest cities in terms of the indicator under consideration.

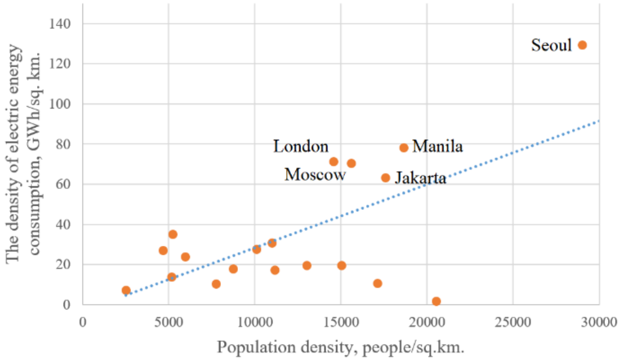


**Fig. 9.** The density of electricity consumption of population (GWh/km$^2$).

Table 2 presents 5 groups of urban metabolism factors: energy, climate, environmental, municipal and economic.

**Table 2.** Groups of factors of the metabolic profile of the city

| Groups of factors | Factors |
|---|---|
| Energy | Consumption of electrical energy<br>Energy consumption by mobile units |
| Climate | Solar radiation<br>Precipitation |
| Ecology | Harmful substances emissions<br>Greenhouse gas emissions<br>Greenhouse gas absorption capacity |
| Municipal | Water consumption<br>Solid municipal waste disposal |
| Economy | GDP (gross domestic product)<br>EROI (energy returned on energy invested) |

The factors listed are of interest both in absolute and specific (for example, per capita) terms. At the same time, the key point in building a metabolic profile is the correctness of the initial data, especially when it comes to comparing different cities. This also applies to the collection of information within the framework of environmental reporting of enterprises. Table 3 presents the initial data for the construction of metabolic profiles using the example of two world megacities: London and Moscow, which have comparable indicators for many factors.

It should be noted that in Moscow, the main fuel is natural gas, unlike London, where, along with hydrocarbons, nuclear energy and renewable energy sources are present in the city's balance sheet. Thus, the structure of electricity consumption directly affects the volume of harmful substances and greenhouse gases emissions. In addition, as stated earlier the use of conditionally calculated indicators of greenhouse gas emissions in the coverage areas of large agglomerations does not provide an understanding of the essence of the processes taking place in cities.

**Table 3.** Metabolic values in London and Moscow

| Factors | London<br>(pop.: 12 400 000) [28] | Moscow<br>(pop.: 13 600 000) [28] |
|---|---|---|
| Consumption of electrical energy, TJ (GW·h) [28] | 143 804.67<br>(39 945.74) | 187 035.48<br>(51 954.30) |
| Energy consumption by mobile units, TJ [28] | 182 955.66 | 263 052.06 |
| Solar radiation, kW·h/m$^2$ [28] | 1 050.00 | 1 020.70 |
| Precipitation, mm [28] | 601.00 | 698.00 |
| Harmful substances emissions | n/a | n/a |
| Greenhouse gas emissions, mln. tonnes/year [29, 30] | 70.00 | 120.00 |
| Greenhouse gas absorption capacity | n/a | n/a |
| Water consumption, mln. m$^3$ [28] | 707.27 | 1 496.00 |
| Solid municipal waste disposal, th. tonnes [28] | 1 696.00 | 4 003.20 |
| GDP (gross domestic product), mln. USD [28] | 386 900.00 | 664 420.00 |
| EROI (energy returned on energy invested) [13, 18] | 33.6 | 74.0 |

***Acknowledgement:*** *This study is financed by the European Union-NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project № BG-RRP-2.013-0001-C01.*

## CONCLUSIONS

EROI is a fairly specific energy indicator at the intersection of technical, economic and social sciences. Its usage to date is determined by two limitations: the development of correct calculation and forecasting methods, as well as the determination of the limits of practical applicability. This article proposes a solution to the second limitation, namely, the calculation of the weighted average EROI of a city's electrical energy consumption system. This value can be useful in the analysis of the fuel and energy balance, economic development potential and sustainability of a city energy system.

At the same time, an increase in the share of energy resources with low EROI in a city’s balance, for example, as part of a “green” energy transition, can lead to a decrease in the level of urban metabolism of the city and a drop in the weighted average EROI to socially and industrially significant values. A potential task is to build a metabolic profile of cities and search for reserves for energy saving, including taking into account the current and future values of a city’s EROI.

Promising areas for the study of urban metabolism include:

- Calculation of the fuel and energy balances of cities, considering the dynamics they are under in the context of the last 10-25 years.
- Development of a list of absolute and specific criteria for the typologization of cities.
- Building models for predicting the level of metabolism and a list of strategic activities for groups of cities with similar energy and environmental profiles.
- Assessment of the energy saving potential in urban energy.
- Search for avenues to improve the environmental characteristics of enterprises and their involvement in the fuel and energy balance of a city.

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