A methodology for planning the efficiency of energy resources within the regional economic system

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Abstract. Changes in the competitive environment and the emergence of complex hierarchical interrelationships within the organizational system of the power economy complicate the process of making decisions in the area of planning and forecasting energy consumption. In such conditions, the economic system is not always able to use to a maximum the available energy resources and brings about system-wide "value losses" which reduce the efficiency of the economic system. The economic system cannot be equilibrated and balanced and constantly produces entropy. The existing methodology for planning and forecasting energy consumption, which is based on the application of average statistical indicators, does not meet modern requirements for the effective management of energy resources.

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Introduction

The operation of the complex open regional economic system is currently characterized by changes in the features of vertical and horizontal integrity, complex hierarchical interrelationships, and the augmentation of the emergentness and multiplicity of the description of all of the system's features and parameters, which are under the influence of backbone factors forming complex information-economic interrelationships within the management system.

The restructuring of the power sector and complex economic systems have brought about the functional economic insularity of entities within the regional energy-economic system, creating a precondition for the formation of a multi-dimensional system of managing the economy and an objective need for enhancing the methodological fundamentals of planning and forecasting energy consumption, which are predicated on the principles of formation of multi-agent economic systems, the theory of fuzzy logic, and the theory of intellectual and genetic algorithms.

Theoretical tenets and methods

The authors' approach towards the development of a methodology for planning energy consumption within the regional economy is predicated on the following theoretical tenets.

The management of open economic systems possesses multi-functionality and complexness: it is inclusive of the proportions of the development of many heterogeneous elements of the system, the formation of new organizational systems and production facilities within the energy economy, the mobility of the structure of markets and changes in the competitive environment, and the dynamism of changes in the structure and composition of energy resources consumed [1]. In such conditions, the economic system is not always able to use to a maximum the available resources, possesses a side effect characterized by the consumption of energy resources without creating a useful way out, and brings about infrastructural "value losses" which reduce the efficiency of the economic system [1]. Such a state of the open economic system cannot be equilibrated and balanced and constantly produces entropy.

Many scientific publications [2,3,4,5] have noted that in modern conditions statistical methods of analyzing and forecasting economic indicators do not comport with modern economic realities, and this is associated with the non-Gaussian-ness of distribution of the characteristics of quantities analyzed. In particular, it has been noted that the mean values of economically significant indicators do not allow us to adequately reflect the state of economic development and oftentimes lead to a decline in the quality of the planning system. American mathematician B. Mandelbrot has examined examples of non-Gaussian distributions and the limitedness of application of Gaussian approximations in a great number of cases.

Worthy of particular mention is the cenological approach towards the analysis of complex systems, which was proposed by B.I. Kudrin, and the related various and numerous applications of it in particular sectors of knowledge, based on hyperbolic distributions. Hyperbolic distributions are widely common in nature and society, yet no single opinion on causes behind their being common has been worked out yet. Our review provides references to over 10 variants for substantiating the primal cause behind the emergence of hyperbolic laws.

The author's methodology

The author's methodology for planning and forecasting energy consumption by the region's economy is predicated on the principles of the economic cenoses (a feature of the evolution of complex economic systems, which forms the basis of the development of the theory of utility) and Pareto efficiency.

Processes of material production and economic development are linked with energy consumption volumes and are accompanied by an increase in entropy. The proposed methodology is grounded in the entropic economic-mathematical model for the interrelationship between the region's energy consumption and Gross Regional Product (GRP). A criterion for the quantitative assessment of economic development is *GRP entropy accrual.*

The ranked diversity of energy resource consumers is governed by the hyperbolic law. Changes in cycles of economic development, structural shifts, and growth in competition and the formation of new market segments are characterized by dynamism and constantly change, but hyperbolic dependencies persist, with energy consumption and increase in entropy being significant conditions. Note that both energy and entropy are construed here in a thermodynamic sense, which does not contradict the principles of the methodology of formation and planning of "useful energy" based on the balance method.

Despite a formal similarity between thermodynamic entropy and Shannon entropy (information entropy), as well as the existence of a great many publications that equate these two concepts, it is the computation of thermodynamic entropy for macro-systems that appears to be a labor-intensive, at times unsolvable problem. In his monograph, D.S. Chernavsky provides quite a full analysis of comparing the two types of entropy and demonstrates that these two concepts are not identical. The comparison of thermodynamic and information entropy becomes possible only at a micro-level corresponding to the interaction of molecules; there has been derived a formula for a match between the accruals of information and thermodynamic entropy.

We should point up one more feature of energy-economic systems inherent in cenoses – fractality. This feature has been noted by many authors [6,7]; a number of authors see in this the reason behind hyperbolic laws being common. The ranking of the statistical distribution of the *energy consumption* of specific enterprises and organizations based on a particular attribute leads to the emergence of hyperbolic laws (bio cenoses, techno cenoses, Pareto's Law, Zipf's Law) and is characterized by sustainability [8]. B. Mandelbrot's mathematical rationale for Zipf's Law is constructed on the basis of simple admissions – therefore, due to the significance of this construction for substantiating the proposed model let us examine the major admissions and stages in this proof.

The probability of the word p_m with a length of m letters appearing can be presented in the following form:

$$p_m = p_0 \exp(-\beta m) = Pr^{-B}, \quad (1)$$

where $B = \beta / \log M$ and $P = p_0 (M-1)^{\beta}$

The authors believe that the application of B. Mandelbrot's theoretical tenets lies in the following.

The power (hyperbolic) law of distribution of an energy resource consumed, which is derived in admitting the equiprobable emergence of all economic entities as consumers, marks the consumer out as a singular entity within the economic system, which has the energy consumption rank r and is perceived not as some sequence in consumption but as an entity that has an independent energy-economic significance.

Thus, in accordance with the principle of free access to energy resources, there is to be an equal probability of energy consumption by some separately taken singular consumer *m* (an enterprise or an organization) within a community of *M* economic entities in the region. The probability of isolation of the singular consumer equals p_0.

The likelihood of the consumer standing out in accordance with this attribute, on the one hand, determines the possibility of isolation of the consumer as an economic entity and, on the other, is actually one of the attributes of the feature of fractality (the absence of a stringently established definition and probability).

In relation to the rank analysis of energy consumption by the region's economic entities, the realization of the author's theoretical tenets is effected in the following way. Those ranked by common attribute – the consumption of an energy resource by economic entities forming types of economic activity and characterized by mean indicators of activity (energy consumption, Gross Regional Product, etc.), form the weights of ranks in the aspect analyzed, with subsequent normalization. The number of enterprises included in the rank is represented by a vector whose length, in accordance with available statistical data, corresponds to the number of enterprises. The scaling of the vector (rank) is chosen depending on the scale of the region which numbers in tens and hundreds of thousands of enterprises/consumers. Based on the normalization of weighted indicators to one, one constructs a cenoses type step distribution function, which is approximated by a hyperbolic type function $y = ax^{-\beta}$, forming an integral energy-economic cenoses (distribution of the total volume of an energy resource across groups of energy consumers within the economic system) of the region (Figure 1).

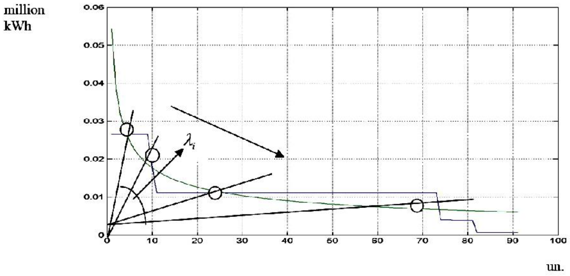


Figure 1. A rank distribution of energy consumption by economic entities engaged in major types of economic activity within the region and an integral energy-economic cenoses

One should approximate the step function not by the criterion minimizing the curve's root-mean-square deviation from the step function but by the proposed integral criterion, which minimizes the difference of the areas under the broken-line and approximating hyperbolic type function. The proposed formal criterion for integral energy consumption by the region has the following form:

$$F\min = \min[\sum_{i=1}^{N} Fi(i) - \sum_{i=1}^{N} y(i)]^{2}, \quad (2)$$

where $Fi(i)$ is an aggregate of mean values within the ranked sample;

$y(i)$ is an aggregate of discrete values of the approximating function;

N is the full volume of the sample under examination

Note: the relative error of approximation by the given criterion does not exceed the 10^{-4} order value.

The integral energy-economic cenoses is based on the definition of the function of theoretical energy consumption by the region's enterprises and does not contradict the fundamental principles of the methodology of energy-balance and the formation of useful energy, which, in our view, can be presented in the following form:

$$E_t \sum_{1}^{i=n} \int_{k_{i\min}}^{k_{i\max}} \grave{A}_0 \cdot \tilde{o}^{-\beta} dx \approx \sum_{1}^{i=n} E_{ti}, \quad (3)$$

where E_t is the total volume of consumption of an energy resource by the region's economy in the period t;

E_{it} is the consumption of an energy resource by consumers forming ranks on i types of economic activity;

k_{imin}; k_{imax} are the boundaries of the rank (the minimal value of the first consumer is $1x10^{-3}$);

A_0 is a constant coefficient characterizing the existing technical level of energy resource consumption

To analyze structural changes in the region's economy and shifts in energy consumption, one needs to be guided by the fundamental principle of the equal utility of the integral energy-economic cenoses and the author's principle of marking out "value losses" of an energy resource, the formalized criterion for which has the following form:

$$\mathring{A}_t \int_{k_{i\min}}^{k_{i\max}} \grave{A}_0 \cdot \tilde{o}^{-\beta} dx \geq / \leq E_{t_i},$$

consequently $\mathring{A}_t \int_{k_{i\min}}^{k_{i\max}} \grave{A}_0 \cdot \tilde{o}^{-\beta} dx - E_{t_i} \approx \pm\Delta\mathring{A}_{t_i}$ (4)

The distribution of "value losses" $\pm\Delta\mathring{A}_t$ is determined by the limiting value of enterprises' structural shifts $\frac{\partial \acute{o}}{\partial \tilde{o}} = \lambda_i$ =>max [4] (Figure 1), which lets us determine the state of the energy consumption system, forecast and plan the volumes of energy resource consumption based on the realization of Pareto's Principle and changes in the structure of business entities in the region's economy, being, in essence, the global goal-setting criterion for the distribution of the energy resource in a long-term period.

The derived function of the integral energy-economic cenoses, which is a cenoses type function and possesses self-similarity features; lets us apply the methodology of fractal analysis – namely, entropic criteria – for the purposes of planning energy consumption by the region's economy.

The hyperbolic law characterizes asymptotic ranked distribution corresponding to the equiprobable distribution of an infinite number of consumers. The baseline step function is interpreted at horizontal intervals as an aggregate of objects which on average possess an equal probability of energy consumption. The probability $p(r)$ at $r = 1 \ldots N$ within the limits of each rank is interpreted as the probability of the existence of a working enterprise possessing a medium level of energy resource consumption within the limits of the rank [9;10]. The energy consumer as an economic entity is preserved in the economic system but in a different upgraded capacity. The ranks' boundaries are mobile and "blurred".

Thus, there intrinsically emerge preconditions for the optimal planning of energy resources and managing of the structure of the energy consumption, GRP, and energy-intensity of the regional economy.

The rationales provided by the authors let us apply the measure of Shannon's information for the development of an optimization model for the distribution of energy-consuming entities taking part in the formation of the region's GRP. Note that it appears possible to apply the approach proposed by B. Mandelbrot for the optimization of the channel of transfer of information through coding text messages using words with a minimal average number of letters per word.

The probability of energy-consuming entities characterized by equal average energy consumption should take the following form:

$$\sum_{i=1}^{N} p_i(r) = 1 \quad (5)$$

Note that enterprises with equal average energy consumption will be characterized by a similar probability.

Shannon entropy in this case will take the traditional form $H = -\sum_{i=1}^{N} p_i(r) \log_2 p_i(r)$ (6)

To minimize the rank, the weighted probability EM at the fixed quantity of H is determined based on the criterion proposed by B. Mandelbrot:

$$EM = \sum_{r=1}^{R} p(r) m(r), \quad (7)$$

where R is the total number of the region's enterprises;

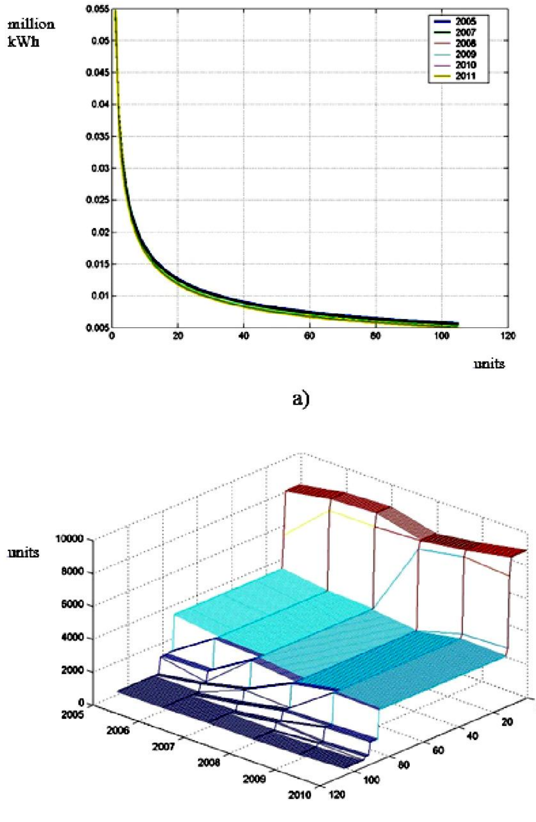
m_r is energy consumption across the ranks

The formula (7) lets us minimize the number of enterprises with the equal average energy consumption of the rank and redistribute energy-consuming entities across the ranks in accordance with the volume of GRP produced. Note that here it appears possible to apply C. Shannon's fundamental tenets for the purposes of optimizing the regional economic structure and determining the minimal average number of economic entities across the ranks.

Testing and results

The results of testing the proposed methodological fundamentals using data related to electrical energy consumption by economic entities within one of Russia's regions are provided below.

We used as baseline data from official statistical data-books, from which we took the indicators for the region's development dynamics for 2005-2011: energy consumption and GRP volumes.



a)

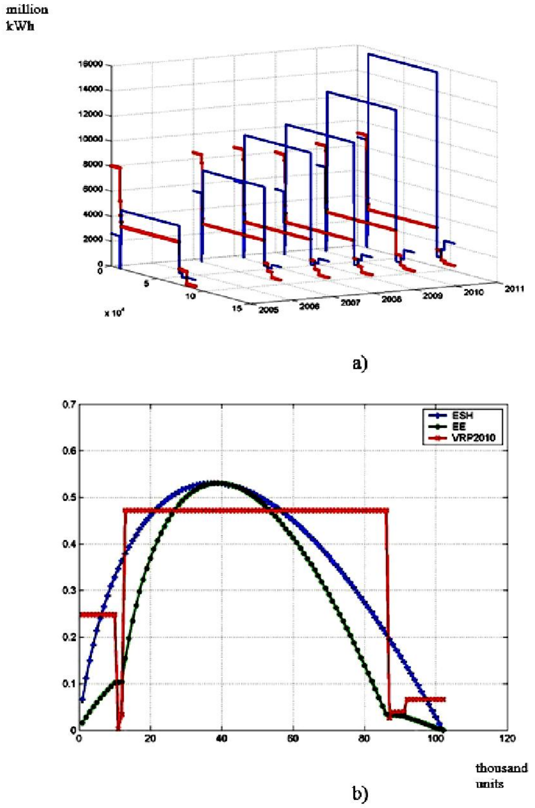
b)

Figure 2. A more demonstrable presentation of the dynamics of changes in the number of enterprises by years

We ranked the region's enterprises into 8 ranks by electrical energy consumption volumes (in accordance with the balance of useful energy distribution), constructed integral energy-economic cenoses functions, and determined the parameters of the hyperbolic law. In accordance with the conducted ranking by electrical energy consumption, we calculated the mean GRP values on each of the groups.

An analysis of comparing the energy consumption graphs for the period under examination (Figure 2, a) demonstrates their practical merging, which indicates that despite changes in the number of enterprises by years (Figure 2, b), the structure of the region's economy does not change much overall. We do not observe a dynamics of changes in energy consumption volumes.

The graphs below (Figure 3) provide the scaled values of the GRP indicators for 2005-2011 for ≈ 100000enterprises in the region (Figure 3, a), which correspond to the electrical energy consumption ranks.



a)

b)

Figure 3. The dynamics of GRP and energy consumption by the region across the ranks and the probability of GRP production by the region's enterprises

We combine with the GRP graphs ($GRP2005-2011$) the normalized graphs for the probability of Shannon entropy (ESH) (the external curve) (Figure 3, b), which are computed for the equiprobable distribution of enterprises, as well as the graphs for the probability of Shannon entropy computed for the groups of enterprises ranked by the quantity of average energy consumption (AEC) (the internal curve), reflecting actual and irreversible processes taking place in the region's economy.

The graphs provided in Figure 3 demonstrate that ranking enterprises by the quantity of average energy consumption lets us establish the direct proportional link between the quantity of the GRP volume within the limits of the energy consumption rank and *entropy accrual,* since the mean value of the volume of GRP production is proportional to the area under the horizontal intervals of the broken GRP curve and is a specific value. The area confined by the two graphs indicates the possibility of an additional volume of GRP production through the minimization of "value losses" and an optimal structure of energy consumption [11;12]. The above graphs also indicate that the marginal volume of GRP production can be attained only when the distribution of energy consumption asymptotically tends to the hyperbolic law and forms an integral energy-economic cenoses. The number of enterprises is great, and the entire economy is represented by an aggregate of separate enterprises (entities), which are characterized by an equal probability of energy consumption and equal access to the consumption of energy resources.

Entropy accrual within the limits of the rank is a specific value. Consequently, the author proposes the following formula, which links GRP with the ranked consumption of the energy resource:

$$\text{深?} \quad = \sum_{r=1}^{N} m(r) \cdot \delta I(r), \quad (8)$$

where $\delta I(r)$ is entropy accrual within the limits of the rank; $m(r)$ is the weight coefficient linked with the efficiency of the use of energy; N is the number of ranks

The weight coefficients $m(r)$ are determined as coefficients for the correlation of the ranked indicators of GRP and entropy accrual for each rank of energy consumption by the region's economic entities.

For the purposes of forecasting and planning the indicators of the efficiency of the use of energy resources, considering the re-distribution of "value losses" of the energy resource consumed and based on (7); (9), we form an additional GRP increase. Based on the formulas (7), (9), and (5), changes in GRP energy-intensity are determined using the following formula:

$$\Delta \xi_i = \frac{\partial \text{深?} \quad {}_{\mathrm{ti}}}{\partial E_{ti}} \quad (9)$$

For the purposes of fine-tuning the indicator ξ_i, one needs to take into account the impact of a set of regional factors:

∂淶? $=\left\{\tilde{o}_1, l \in L\right\}$, where L is a set of regional factors of the type *l(10)*

Conclusion

The proposed integrated model constructed based on ranking the region's enterprises and organizations by the level of energy consumption forms an integral energy economic cenoses which is governed by the hyperbolic law, possesses fractal features, and comports with the principle of maximum entropy.

The realization of the author's methodology for planning and forecasting energy resource consumption involves the following stages:

- Ranking the region's consumers by average statistical indicators of energy consumption.
- Constructing an integral energy-economic cenoses on energy consumption and identifying "value losses" based on Pareto's Principle.
- Ranking GRP by the energy consumption ranks.
- Variations of planning energy consumption in accordance with the ranks marked out (the ranks' boundaries are "blurred").
- Determining the weight coefficients $m(r)$, which link GRP with the corresponding energy consumption ranks and rationally changing the distribution of the energy resource between the ranks for the purposes of attaining the planned GRP indicators.

The authors believe that the proposed methodology makes it possible to come to the conclusion that the cenoses approach towards the construction of a model for the regional economy's energy consumption requires reconsidering its features as a complex organizational-economic and techno-technical system characterized by the impermanence of the number of entities/consumers and the existence of flexible structural boundaries and open economic relations. The model developed by the authors is a whole new approach towards the analysis, forecasting, and planning of energy consumption for a long-term period and substantiated goal-setting with regards to the region's economic development.

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