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ENERGY EFFICIENCY OF CONSUMPTION – METHODS OF ANALYSIS AND EVALUATION

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ABSTRACT. Technical, economic, and social need to define and control the efficiency of energy usage – consumer energy efficiency implies the necessity to determine the exact contents of this new concept. A deeper analysis of a consumer energy system in order to support the consumer energy efficiency value appropriate for the contents should be carried out to find the factors that affect the value. This article shows that for the purposes of advanced energy consumption analysis, the consumer energy system becomes an integral part of the whole energy system (starting with the energy generation facility) which forms the demand for the produced energy and its usage efficiency. The consumer energy system is so important that in the course of developing and improving the electric supply and consumption systems, it questions the traditional priority of the first component (energy supply) and adaptive dependence of the second one. This article proves, inter alia, that manufacturers can raise their consumer energy efficiency by improving the production technology, using materials with new properties, modernizing the energy equipment, switching to automatic enterprise design systems and using other means commonly known as scientific and technical progress.

Introduction

Generally, material production implies to manufacturing a product by means of energy use. This approach corresponds to the currently accepted (free-market-driven) consumer energy efficiency (EE) index (Nur *et al*., 2015; Fazek *et al.*, 2017) defined as specific energy consumption per unit of the manufactured product and per unit of earning received from the sales of a product. A reasonable question is how the amount of energy consumed and the amount of the product manufactured are inter-connected within a company. If there is any straightforward relation, then it would be possible to find a function and analyze it in various manufacturing conditions. Another extremity is the eventually used approximation, not as an analytical method but as a way of reporting, which does not include any information required to manage the EE. This is understandable, as it is quite difficult to find an easy way to analyze EE due to many reasons the most important of which are: the use of various types of energy, co-existence of two energy-related terms (energy and power) (Allik, Annuk, 2017), great variety of technical equipment processing energy (Maheswaran *et al.*, 2012; Huawei, Wen, 2011) (transmission, changes of the energy parameters, energy transformation from one type into another, *etc*.), energy effect on various environments and objects (Zheng *et al.,* 2014; Kolozali *et al.*, 2016).

To get a comprehensive presentation of the variety of the processes and the types of energy and equipment involved in farming, it is sufficient to divide the processes into static and mobile. Additionally, all energy processes include energy losses, which cannot be directly measured. Therefore, the methods of mathematical analysis, -which are a part of the theory of functions and widely used in engineering practice, need adaptation to the conditions and tasks requiring solutions within the framework of a consumer energy field.

System approach, determined by production technology, is the basic generalization condition of the analysis. Production technology defines energy application processes and the types of energy equipment. The selection of equipment is an important stage, which affects energy efficiency. Professionally, the correct selection is made by determining nominal power, which corresponds to the maximum load. The reason for this choice is the necessity to ensure equipment-operating stability in all possible operating modes. However, because of this choice, the data becomes too indefinite to use it for the purposes of describing, analyzing and controlling the technical part of the company's energy installation.

Nevertheless, there is no reason to change this equipment selection approach, as the technical basis of energy installation, thus created, really ensures reliable system operation. Therefore, it is necessary to search for more opportunities to improve the technical basis taking into account the modern requirements of energy usage, new energy measuring techniques, and information technologies.

The first attempts to search for solutions (Karpov, 1999) used energy processes which take place in each technical element (TE) and which are available for measuring both, energy increase (integral index, numbers) when passing through a TE and the changes of power as a function of time. That is why it is possible to use not only the law of storage conservation of energy but also the higher mathematical theorems on the function differentiability for the purposes of the analysis. Adding energy-technological processes (ETPs) to the end of each consumer's energy efficiency (CES) energy line (Figure 1) allowed introducing a new concept – the result of energy operation where the numeric value of the result is defined by the technological requirements of the production process.

Generally, the available scientific physical knowledge is sufficient to calculate the amount of energy required to obtain the result (minimal amount without losses), which makes the EE calculation in ETPs comparative and its numeric value limited on one side. Besides, the use of ETP entails the inclusion of physical values and regularities, which complement the technical basis with the theory of the processes in the energy consumption analysis. Firstly, the peculiarities of the mathematical analysis of energy processes are considered.

The aim of the research was to give an overview of the features of the mathematical analysis of energy processes.

Methods

There are two energy terms – energy Q and power P, which are mathematically related.

Power P is a function of energy, *i.e.* $P = dQ\,dt^{-1}$, while energy can be defined by integrating the power-dependent expression $dQ = Pdt$ as $Q = \int P(t)dt$.

Modern measuring techniques allow to obtain the integral as, for example, the reading of an energy meter. Seemingly, it opens new possibilities for mathematical analysis of energy processes. Still, the meters integrate the values by adding-up the discrete values of energy increases, which means that the function is not used, and the mathematical analysis methods are inapplicable. Nevertheless, energy function can be differentiated by finding the average power $P_{av} = Q\,t^{-1}$.

However, this procedure requires special attention. The matter is that $Q(t)$ function is time-ascending in Cartesian coordinates, but any period of time may include horizontal sections, *i.e.* zero power, which do not affect the meter readings but may affect the results of the analysis reducing the average value.

Another substantial peculiarity of CES energy parameters is their (both power and energy) inter-connection with the specifications of the technical elements which are specially selected to perform the energy processes under specific manufacturing technology.

The most common processes and corresponding TEs include energy transmission by conductors to the point of destination, transformation of energy parameters (for electric energy – single- or three-phase current or voltage, for heat energy – temperature and pressure), energy transformation from one type into another (various transformers), ETPs), final energy lines of CES), special effect of various energies or power on technological mediums and objects with the aim to obtain the final numerical results (integral or differential), as required by applicable technology.

The above-mentioned processes are either transitional (energy passes through TEs) and terminal (where energy movement through CES ends).

An empirical experiment (water heating with electric power) to demonstrate the formation of EE index is given as an example below.

First, the amount of energy required obtaining the expected result (new property of water) – final water temperature has to be calculated. Heat formula from physics can be used:

$$Q = cm(T_{fin} - T_{start}), \qquad (1)$$

where m — water mass; c — the specific heat of the water.

T – temperature C^0 (the capital letter is used to distinguish from the time designation).

Assuming that water weight and 'c' are constant, we multiply the values and define the result as Q^{SP}. Then, the formula will read:

$$Q = Q^{SP}(T_{fin} - T_{start}) \qquad (2)$$

This formula is of primary importance for EE. Firstly, because energy calculation is specific for production technology (technology defines the value of T_{fin}), secondly, the formula does not consider energy losses, and therefore the result shows the minimum energy required heating up the given amount of water, thirdly, we get a coefficient between energy and temperature increase. For the purposes of generalizing, the difference in temperature T (the result of the procedure) is defined.

By introducing the effect of energy application at the end of the energy line in the CES processes analyses, by the means of simple calculation, a primary (for the whole energy system) numeric value of the energy demand for the specific ETP is obtained. However, the value is introduced as energy units only without any relation thereof to power and time required to receive the result. Since the Q calculation does not include energy losses, (from an energy efficiency point of view), the obtained value corresponds to the maximum efficiency of the process.

Therefore, ETP as the energy-demand maker returns a limiting (minimal) value of energy, which can be used to compare with other values, obtained in the process of the equipment operation. As the heater is a real technical device (we have a tubular electric heater with a known constant power capacity P, which is technical value, *i.e.* not determined by function differentiation or by measurement), it is possible to calculate the heating time t (minimal). If in the course of the experiment the result R (consuming the input energy) is kept under control, any deviation from the pre-calculated values may be explained by losses, which cannot be determined by calculations or direct measurements.

It should be highlighted that introducing ETPs in CES makes it possible not only to monitor adherence to the technological procedure with technical means (measurements) but also to minimize the process uncertainty, which affects the energy usage efficiency control.

The water heating experiments conducted showed that the actual heating time and energy consumption were higher than the pre-calculated values.

Since it was an empirical experiment, we attempted to register the growth curve $R(t)$. Due to the physical reasons, it was not possible to register the whole curve, but we managed to register the end section of the curve with the non-linear part. It allowed to linearize the process of the action result growth and receive the average growth speed value R', which formed a differential disparity when compared to the calculated average speed:

$$R' = Q\,t^{-1},\ t = Q\,P^{-1} \tag{3}$$

The general result of the experiment, when compared to the pre-calculated data, was that the resultant growth speed decreased and the energy consumption and time to achieve the result increased. The numeric values obtained made it possible to calculate the negative increase of the power supplied into the process $-\Delta P_n$ (i.e. the lost power), using the formula:

$$-\Delta P_n = Q^{SP}\left(R' - R'_{AV}\right)\ or\ -\Delta P_n = Q^{SP}\Delta R' \tag{4}$$

Taking into account the process duration $(t + \Delta t)$, we can also find a negative increase in the energy power action using a similar formula $\Delta P_a = Q^{SP}\Delta R'$. Thus, we obtained the numeric evidence that the lost power increase equals the action increase. The analysis of the limiting values of these factors gives the following results:

$$\begin{gathered} for\ \Delta t \to 0\ R'_{AV} \to R', and\ if\ \Delta t \to t, \\ then\ R'_{AV} \to 0.5R'\ and\ P_{A\,AV} \to 0.5P_A \end{gathered} \tag{5}$$

Measuring the amount of energy supplied to the heated water allowed to define (immediately after the end of the experiment) the losses as the difference $Q_{suppl} - Q = \Delta Q$, which justified the qualification of the experiment as an empirical one, i.e. bringing new knowledge, in particular, about the efficiency of energy use.

This brief summary of the experiment confirms that it is expedient to introduce the concept of energy action, as this is the property of energy, which is widely studied and allows getting the minimal value of the energy contents of the result by means of calculation. This energy content is primary within CES and unbiased scientifically. The totality of energy contents of all CES results sums up, finally, in the energy contents of the company's final product.

This latter factor makes energy efficiency increase the internal task of the management and the professional duty of the company's energy department. Attention should be drawn to other Q^{SP} characteristics in addition to its unbiased value. Firstly, it is indifferent, i.e. the factor is proportional to numeric values (and, hence, the function) of both energy and power.

The above-described experiment showed that the losses reduce the effective energy, therefore the time (duration) of the energy-technological process increases in inverse proportion to the losses. The introduction of the 'effective energy' concept in CES defines both the calculated minimum of the energy consumption and other limitations significant for EE.

Still, the analytical possibilities of function differentiation offer more than that. Since no company covers all the target energy consumption fields (social, domestic, cultural, security, *etc.*), then a parameter summarising the consumption of all types of energies within a territory (both industrial and other) may be more appropriate.

Besides, it would be useful to switch from a product energy contents to another parameter, which includes investment payback, *i.e.* find a relation between the consumed energy and the profit. Thus, a formula of gross product energy contents would be:

$$Q_{GP} = \left(Q_{gas} + Q_{oil} + Q_{el}\right)\left(\sum profit\right)^{-1}, \tag{6}$$

where the energy contents of the companies' products play a key role. Therefore, the CES diagram in Figure 1 should be analysed and explained what part of the energy contents of each company is included in the gross product energy contents formula.

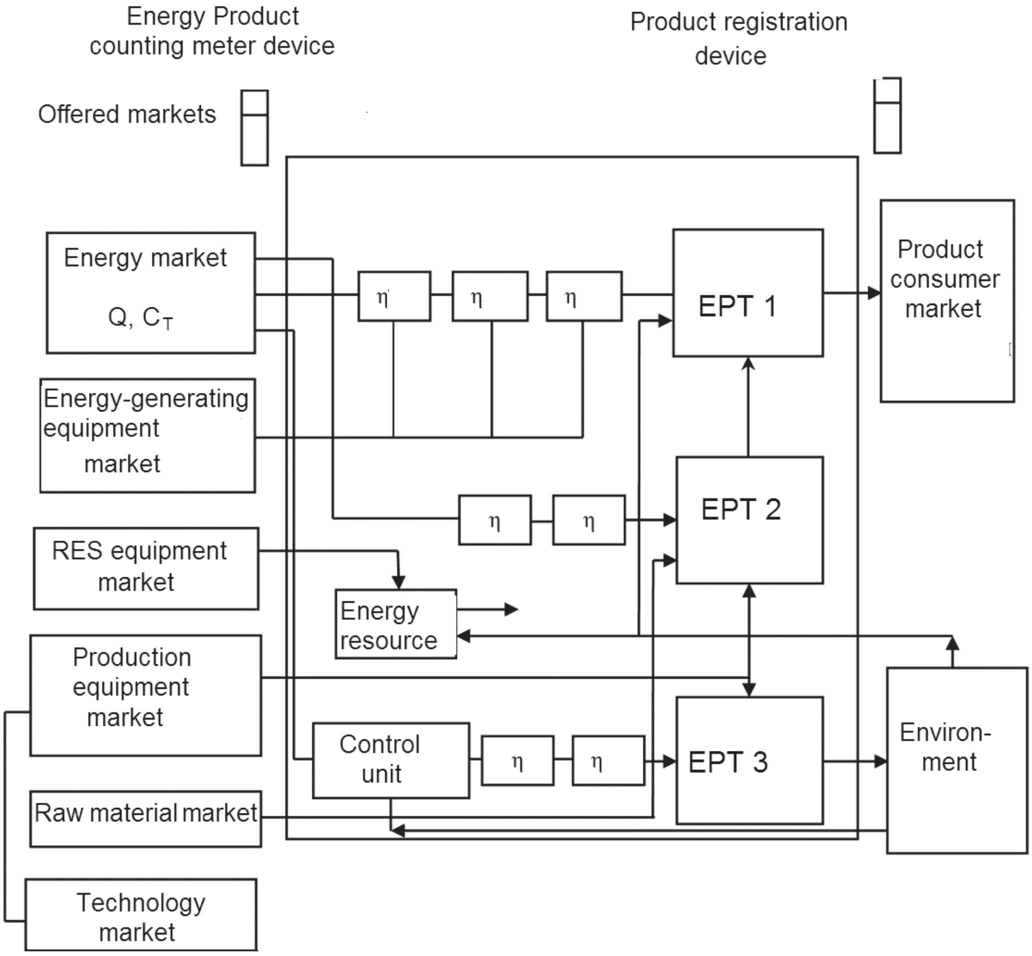

Figure 1. Energy diagram of CES

Results and discussion

This article proves that in any ETP the supplied energy is divided into effective energy, which produces the expected technological result and losses. For the purposes of the experiment, the ways to reduce the losses in order to increase the EE can be found by analyzing the grounds for the technical values included in the technology, hot water usage mode, presence or absence of heater body thermal insulation, body shape.

If any mistakes or inaccuracies in the design are found and analyzed, they should be rectified at this stage. The selection of energy equipment should be analyzed for both the expected nominal power and EE. It is always possible to choose equipment made of modern, energy-efficient materials.

This approach corresponds to the integral design and sustainable development principles as formulated by researchers Stasinopoulos *et al.* (2008).

It should also be noted that the totality of the effective energy and losses is supplied to CES from the incoming panel with a meter installed and then to ETP by the line, composed of TE, each of which creates its own losses. The energy measured with the meter at the beginning of the line is the energy supplied to ETP multiplied by relative energy contents of all TEs in the line (Karpov, Yuldashev, 2010; Karpov, Kabanen, 2018). In order to determine the losses, the active energy should be deducted from this multiplication. Thus, for the purposes of a product energy contents calculation, the sum of the meters' readings can be defined by the separate sums of effective energy and losses.

The CES diagram and the above-described transition from the energy supplied to ETP to the energy measured by the meter prove that both effective energy and ETP losses should be multiplied by the energy contents of the line. Therefore, within the framework of CES, the table-based value of the resulting energy contents (Q^{SP} in our experiment) will increase due to the losses in ETP and the technical line supplying the energy. The amount of the increase can be found using the energy diagram of the finite relations method (Karpov, Kabanen, 2018).

The importance of this explanation is that it reveals the necessity to introduce the physical concept of energy action in CES only (it cannot be found at any section of the line before CES) and determines the reason for the primary increase of energy contents as a part of general increase of a product energy contents increase within CES.

The product energy contents (including action energy) can be found by dividing separately the sum of the effective energies and the sum of losses by the amount of the product. The first quotient would mean the minimal system energy contents and maximum specific (per unit of product) efficiency of energy usage.

Since economic researches have introduced the 'non-economical production growth' (Daily, 2005) and the above-mentioned formula of the gross product energy contents establishes the relation between it and the amount of the consumed energy, then the analysis methods described in this article allow to calculate the numeric value of the share of consumed energy which exceeds the energy contents and has to be reduced.

Conclusion

The mathematical analysis of energy processes proved that the consumer energy system plays a crucial role in monitoring and controlling the energy use efficiency. The layout of a consumer system has to include energy-technological processes. This requirement implies to changing the company design procedure, as it is necessary to reduce the company energy contents in order to ensure its sustainable development by targeted (for each TE) monitoring of loss growth and managing these losses. The article reveals a rather complicated mechanism of information collected about the existing company's energy contents value, therefore the design stage should include informational and measurement system, data collection, and the processsing unit.

As common handling energetic processes proceeded evaluation from an input energy to through efficiency to end used energy. This handling is not allowed to recognize amounts of end used energy. In this approach, in the opposite way, is started evaluation from useful used energy to input energy. This means, that we meter in a process used energy and then some coefficient what take into account efficiency. This approach allows recognizing usefully used energy in the process and then find ways to arise efficiency of the process(es). It is not allowed to evaluate one process, but and also full technology chain.

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Conflict of interest
The authors declare that there is no conflict of interest regarding the publication of this paper.

Author contributions
VK – main author idea of the paper, writing the manuscript;
JZ – writing the manuscript, sampling analysis;
TK – editing and approval final manuscript, idea development.

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