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Dependence Of Energy Efficiency Indices On Individual Energy Technological Protcesses

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ABSTRACT. *An energy system combining various technical elements for a single purpose – manufacturing products –, requires methods taking into account the specifics of systematic combination of its values (efficiency index) for individual elements to specify the general systematic value of the energy efficiency.*
The main difference between of energetic consumption systems (ECS) and transmission systems is the energy technological processes (ETP). In addition to the definition of ECS given above as a process of influencing a specific technological environment with energy to give it new properties or qualities, it should be noted that this process either creates new energy carries or creates new conditions for interaction between this environment and the surroundings, and these possibilities can be combined with different results. It should also be noted that ETPs are usually irreversible processes (except for the increase in potential energy due to work), and the amount of energy received by the new carrier may depend on numerous factors. Nevertheless, the understanding of energy processes in different environments is quite well-developed, and this suggests that values of specific energy per unit of result R are available for common manufacturing processes.
The specificity of the analysed energy processes in the elements of ECS lies not only in their mathematical models. It can be agreed that the model in a form of expression based on the assumption of linearity of the relative reduction of the second energy derivative can be applied both to the transmission elements and the ETP.
In the physical sense, the difference lies in the fact that the energy in the elements of transmissions creates losses (they should be reduced in relation to the transmitted energy) whereas in the ETP, energy creates a result (the amount of absorbed energy should substantially exceed the amount of energy transmitted through the ETP). This difference can be called an inversion of efficiency, and it (the inversion produced in the ETP) must be regarded as a sign of consumer system which is distinctive from the systems of energy generation and transmission.
Keywords: *energy efficiency, economic effectiveness*

I. INTRODUCTION

An energy system combining various technical elements for a single purpose – manufacturing products –, requires methods taking into account the specifics of systematic combination of its values (efficiency index) for individual elements to specify the general systematic value of the energy efficiency.
The main difference between of energetic consumption systems (ECS) and transmission systems is the energy technological processes (ETP). In addition to the definition of PES given above as a process of influencing a specific technological environment with energy to give it new properties or qualities, it should be noted that this process either creates new energy carries or creates new conditions for interaction between this environment and the surroundings, and these possibilities can be combined with different results. It should also be noted that ETPs are usually irreversible processes (except for the increase in potential energy due to work), and the amount of energy received by the new carrier may depend on numerous factors. Nevertheless, the understanding of energy processes in different environments is quite well-developed, and this suggests that values of specific energy Q^{spec} per unit of result R are available for common manufacturing processes.

II. MATERIALS AND METHODS

One of the specificities defined by the general production process is the diversity of the necessary ETP results and the different demand for them. Defined, for example, by the schedule of product output (ETP1) or change of the outside (in relation to the building) air temperature (ETP3). Other features of the ETP zone in the consumer system in relation to the area of power transmission will require use of new mathematical and physical dependences for analysing efficiency.

Classification of ETPs into three types by their functional outcome and aggregation of energy supply to each ETP as a power line composed of successive elements [1] lead to significant simplifications.

If we take into account that the energy consumed by any ETP is a complex function, i.e. it depends on quantitative (integral) value of a result which is a function of time, then considering the possibility of registration of Q(t) and R(t) in the general case, it can be assumed that both parameters determining energy efficiency are defined parametrically. Therefore, the derivative Q'_R (efficiency per se) can be defined as the relationship between parametric derivatives, i.e.:

$$Q_R^{'} = Q_t^{'} \cdot R_t^{'} \quad (1)$$

In fact, the transition from a complex function like $Q = f[R(t)]$, for which by definition $Q_t^{'} = Q_R^{'} \cdot R_t^{'}$ for the expression (1) is obvious, and proofs of transition are given in math textbooks. The main conclusion that follows from this is an experimental theoretical finite ratio method (FRM) [1] designed for the elements transmitting energy and also suitable for energy technological processes with the use of its inherent concepts and parameters (relative energy consumption with respect to energy and power, relative losses, etc.). For example, from (1) we have actual measured power P_φ in the form of an expression:

$$P_\varphi = Q_t^{'} = Q_R^{'} \cdot R_t^{'} . \quad (2)$$

If $Q_R^{'} = Q_R^{spec}$, then $P_\varphi = P_{min}$, and P_{min} corresponds to the theoretical value of Q_R^{spec}, i.e.:

$$P_{\min} = Q_P^{spec} \cdot R^{'} \quad (3)$$

From two last expressions, taking into account that $P_\varphi / P_{min} = Q_E$, we get (relative energy intensity of the result):

$$Q_R^{'} = Q_E \cdot Q_R^{spec} \quad (4)$$

Semantic difference of FRM for energy technological processes from processes in the elements of transmission is that in the second case, the value of Q_K can be regulated by the arbitrary considerations, and in the first, the physical process of creating result. This defines a new professional component of knowledge of a specialist (energy technician) who is engaged in solving energy conservation.

The energetic approach outlined in relation to the ETP forces us take a closer look at the processes in transmission elements, particularly to clarify the possible dependence of Q_K. As a general rule, in addition to main structural components, power equipment has additional ones which directly or indirectly impact the energy process. These additions with different physical properties in relation to the energy flow can be called the element's infrastructure. This may include shell casings, electrical and thermal insulation coatings, devices for the removal of excessive heat, etc. It is important to note that in the current practice of selecting equipment, the influence of energy infrastructure is not taken into account. Let us consider the effect of the infrastructure on the example of two ETPs: heating water in a special container (auxiliary ETP2), and space heating (ETP3 providing the living environment).

Expression for determining the energy consumption for heating water is as follows:

$$Q = Q^{\text{spec}} \cdot V \cdot (T_{\text{final}} - T_{\text{initial}}) \quad (5)$$

where V is the volume of heated water.

It should be noted that the result of the process is T_{final} – final temperature after heating. With a heater at constant power, the increase of T_{final} is linear; therefore, the period of heating is strictly defined (dashed line 1 in Figure 8). However, the actual process of temperature rise will follow the flatter curve 2 and will require more time that will increase the energy consumption proportionally. The registration of the process of temperature rise and its comparison with the linear one (with the constant power of the heater P_{heat}) allows determining the relative power consumption of the process: $Q_E = P_{avg.\varphi}/P_{heat}$. The same ratio for power use is found from formula (5). It is clear that increasing Q_E to above one depends on the degree of insulation of the vessel, i.e. the energy parameters of the infrastructure.

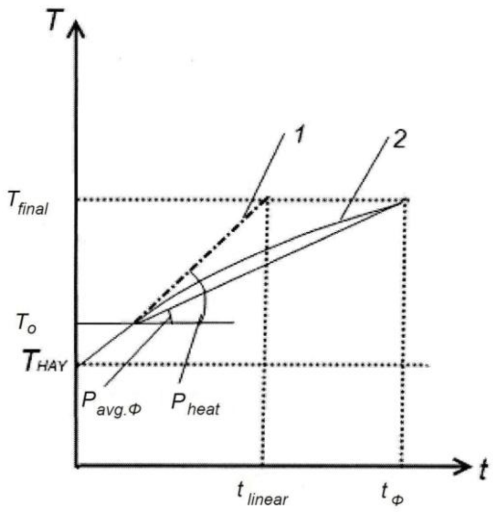

Fig.8

The elements of the energy system may form consecutive and parallel lines. If we assume that energy transmission from the preceding link to the subsequent link in a sequential connection is lossless and losses are accounted for only in the elements themselves, then energy consumption of the whole sequential line will be a product of the energy intensity of all the links, i.e. $Q_E = C \cdot Q_{Ei}$ (where i is the number of units) [2]. For example, for two consecutive links with energy intensity $Q_{E1} = P_{n1}/P_{k1}$ and $Q_{E2} = P_{n2}/P_{k2}$, the overall energy consumption (if $P_{k1} = P_{n2}$) will be as follows:

$$Q_{E1\text{-}2} = P_{n1}/ P_{k2} = Q_{E1} \cdot P_{k1}/ P_{k1}/ Q_{E2} = Q_{E1} \cdot Q_{E2} \tag{6}$$

For a successive chain without energy transformations and process discontinuities (for example, in storage units), energy consumption is a unit less quantity higher than one.
In parallel connections of the units we get a different picture. For example, for the parallel connection of two units with appropriate energy
With parallel connection of the links, we get a different picture. For example, for the parallel connection of two links with respective energy intensity $Q_{E1} = P_{n1}/ P_{k1}$ and $Q_{E2} = P_{n2}/ P_{k2}$, the overall relative energy consumption of the connection is as follows:

$$Q_{E1-2}\frac{P_{n1}+P_{n2}}{P_{k1}+P_{k2}}. \tag{7}$$

In a generalized form:

$$Q_E = \frac{\sum_{i=1}^{n} P_{ni}}{\sum_{i=1}^{n} P_{ki}}. \tag{8}$$

If in a case with two elements where $P_{n1} > P_{n2}$, $P_{k1} > P_{k2}$ and express: $P_{n2} = \alpha_n P_{n1}$ and
$P_{k2} = \alpha_k P_{k1}$, then:

$$Q_{E1-2} = Q_{E1}\left(\frac{1+\alpha_n}{1+\alpha_k}\right). \tag{9}$$

The value of the multiplier in the brackets will be determined by the divergence between the values α_n and α_k.
In general, for a parallel connection of i elements, we get:

$$Q_{E1-i} = Q_{E1}\left(\frac{1+\sum \alpha_{ni}}{1+\sum \alpha_{ki}}\right). \tag{10}$$

If $\Sigma\alpha_n = \Sigma\alpha_k$, then $Q_{E1\text{-}i} = Q_{Ei}$. Hence, in a parallel connection of multiple units with multiple power values at the input and output, the overall energy consumption equals energy consumption of a basic element.
Parallel connection of the elements is typical for stations providing living environments. Consider the example of a power plant providing lighting for a room where gas-discharge lamps of total power equal to P_{gl} and incandescent lamps of total power equal to $P_{ln} = 0{,}5P_{gl}$ are used. Assume that the luminous efficiency of incandescent lamps is 10 times lower than that of gas-discharge lamps. It should also be taken into account that incandescent lamps contribute to the overall lighting which constitutes 1/20 (with power share of 0.5). The overall energy consumption derived from installation of the light energy will be as follows:

$$Q_E = \frac{P_{gl} + 0.5P_{gl}}{F_{gl} + 0.05F_{gl}} = Q_{Egl}\left(\frac{1+0.5}{1+0.05}\right) \approx 1.5Q_{Egl}. \tag{11}$$

If the share of incandescent lamps is increased to 1/2, then energy consumption Q_E will be (at an appropriate ratio between power values of incandescent and gas-discharge lamps 10:1):

$$Q_E = \frac{P_{gl} + 10P_{gl}}{F_{gl} + F_{gl}} = Q_{Egl}\left(\frac{1+10}{1+1}\right) \approx 5.5Q_{Egl} \tag{12}$$

Consider the example of calculating the energy consumption of a consecutive line including an energy converter (nominally, from type 1 to type 2). A schematic of a line consisting of 5 elements (the third element being the converter) is shown in Fig. 1:

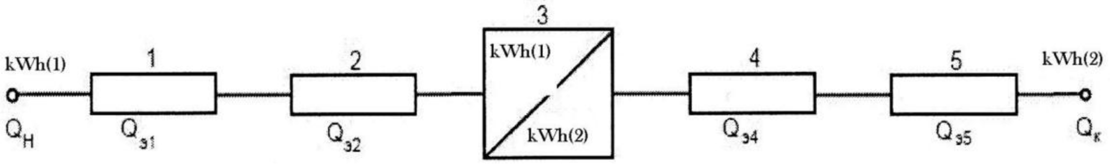

Fig.1. Energy transmission line with consecutive elements

In accordance with the previously obtained rule of calculating energy consumption of the consecutive line, we will write down the following:

$$Q_{E1-5} = Q_{E1} \cdot Q_{E2} \cdot Q_{E3} \cdot Q_{E4} \cdot Q_{E5} \tag{13}$$

For the converter (element 3), the value of input energy Q_{n3} is obtained from the expression
$Q_n = Q_{E1\text{-}2} \cdot Q_{E3}$, kWh (1):

$$Q_{n3} = \frac{Q_n}{Q_{E1-2}}. \tag{14}$$

Similarly, the value of the output energy of the converter is as follows, kWh (2):

$$Q_{k3} = Q_k \cdot Q_{E4\text{-}5} \tag{15}$$

From the general formula of the energy consumption of the element 3, we get, $\frac{kWh(1)}{kWh(2)}$:

$$Q_{E3} = \frac{Q_{n3}}{Q_{k3}} = \frac{Q_n}{Q_{E1-2} \cdot Q_k \cdot Q_{E4-5}}. \tag{16}$$

Hence, the general expression of the energy intensity of the whole line in $\frac{kWh(1)}{kWh(2)}$ is:

$$Q_{E1-5} = \frac{Q_n}{Q_k} = Q_{E1-2} \cdot Q_{E3} \cdot Q_{E4-5} \tag{17}$$

Therefore, the energy converter can be considered an ordinary element.

If at the end of the line there is a technological process with a known energy consumption of the products as a finite element of the chain $Q_E\left[\frac{kWh(2)}{kg}\right]$, then at the end of the expression for $Q_{E1\text{-}5}$ there will appear a multiplier which will translate the units into $\left[\frac{kWh(1)}{kg}\right]$, i.e. complete energy consumption of the products.

Thus, the obtained rules of calculation allow determining the energy consumption of individual elements as well as the whole power line.

Actual estimates of energy consumption upon taking energy-saving measures can be complicated by the fact that, for example, reduction of energy consumption of one element can affect the energy consumption of other consecutive links. However, the measurements and acquired expressions allow considering such functional interdependence of individual elements.

To account for all cases of ETPs typical for ECS, it is important to include the concept of allocated load. An example is the lighting installation in which the lights are usually distributed over the entire illuminated area and form a network of power (group) lines. Without repeating the details of the calculations, we should note the specifics of creating excessive energy consumption. The determining parameter of the minimum energy consumption is the normalized lighting E_{norm}.

With the known area of lighting A, we get the total normalized flow:

$$F_{\sum norm} = A \cdot E_{norm} \tag{18}$$

When choosing the power value of a source P_l, a lamp and calculating their number N, we determine the required power:

$$P = N{\cdot}P_l \tag{19}$$

Using the parameter H of effective output of the source which takes into account the share of luminous flux in the total power $\frac{lm}{W}$, we get the equivalent flow at the input of the lighting installation.-

$$F_n = N \cdot P_l \cdot H \tag{20}$$

The relative energy consumption of the lighting installation is to be determined with respect to the flow:

$$Q_E = \frac{F_n}{F_{\sum norm}} = \frac{N \cdot P_l \cdot H}{A \cdot E_{norm}}. \tag{21}$$

Having denoted $\frac{A \cdot E_{norm}}{H} = P_{norm}$, we get:

$$Q_E = \frac{N \cdot P_l}{P_{norm}}. \tag{22}$$

It should be noted that the expression of the energy consumption does not include the efficient output of the source, even though it is obvious that the impact of this parameter on energy efficiency is significant. The fact is that it is taken into account when the number of sources is determined, i.e. at this stage of design, making an energetically unreasonable decision may lead to energy wastage.

Thus, in this example, relative energy consumption will be determined not only by an obvious parameter (efficient output of the source), but also optimal power allocation, i.e. combination of expertise regarding both lighting and energy during production. A similar situation occurs in heating system calculations: inefficient use may lead to the amount of high-energy fuel being equal to or even exceeding the consumption of low-energy fuel (used efficiently). It should also be noted that the complex spatial distribution of lighting fixtures (in an firm, it may be the installation of greenhouse trays for plant not only horizontally but also vertically) creates an alternative – to spatially allocate the initial (electric) or transformed (flow) energy. The decision related to the right choice will give the value of the minimum relative energy consumption. The need to combine both artificial and natural lighting and take into account the demand for artificial light is a characteristic energy feature of lighting rooms with windows. The inability to automatically control the lighting

installation in accordance with the abovementioned factors creates the basis for inefficient use of energy which should be recorded as the excess of the relative energy consumption over the optimal value.
According to the considered cases of connection of the elements, we can formulate the demands for their energy characteristics meeting which will allow for minimal energy consumption of the processes in the connections:

- consecutively linked elements must have an energy characteristic with a minimal energy consumption close to the linear one;
- elements and lines in parallel connections must have multiple finite parameters with respect to the base element with a minimal energy consumption;
- change of load (P_k) in both cases should be followed with changing the initial power with multiplicative synchronicity, i.e. with the same multiplier.

Fully meeting these requirements is impossible, since they presuppose the constancy of the condition of the element which determines the energy losses in different modes. However, minimal energy consumption is usually known and corresponds to the default mode of the device. Therefore, for energy conservation, it is suitable for an element to consider the default mode as a base mode, and any partial mode is not only to be assessed in relation to the value of relative energy consumption but also compared to the default mode. This technique will allow monitoring not only modally but also chronologically, i.e. during the usage period of the equipment, which gives reason to assign diagnostic function to the energy auditing equipment and put the concept of the life span defined by the maximum relative energy losses into practice of assessing the equipment.
As already indicated, energy efficiency of the processes in an ETP which transmit energy from one carrier to another, following the restrictions on specific values, is a particular challenge. The difference from the usual movement of energy in the element is that to obtain and control the expected material result it is necessary to know the exact allocation of power over the new environment. In the transmitting element, it did not matter, and the equivalent value of power loss which allowed using the method of finite relations was enough. The most telling justification of general ideas is the case of electromagnetic energy entering the structured space of an absorbing environment. For example, let us consider a cylinder through the base of which enters the electromagnetic flow with the power P_0 that does not extend beyond the cylinder. Let us assume that the flow weakens proportionally to the length of the path x while it is absorbed. Then the general expression of the process is as follows:

$$-dP = a \cdot P_0 dx \tag{23}$$

where a is the coefficient of attenuation per unit of length.
Turning to the expression:

$$\frac{dP}{P_O} = (-adx) \tag{24}$$

And integrating it, we get:

$$lnP = -ax + c \tag{25}$$

and

$$P = e^c \cdot e^{-ax} \tag{26}$$

Taking into account that if $x = 0$ $P_0 = e^c$, we ultimately get:

$$P = P_0 \cdot e^{-ax} \tag{27}$$

This expression is useful in that it presupposes the existence of the coefficient a which reflects the ability of the environment to receive the input energy and the definition of which should be a mandatory pre-procedure of a specific technology. Furthermore, this expression is the result of separation of variables and shows the dependence of the change with respect to x of the time derivative of the energy in the form of a share of initial value. If the current value of the power P_x is denoted, the power absorbed by the environment will be equal to:

$$P_x = P_0(1-e^{-ax}) \tag{28}$$

Upon transition to the relative energy intensity of the environment, we get:

$$\frac{P_O}{P_X} = \frac{e^{+ax}}{e^{+ax}-1} \tag{29}$$

It should be noted that if $x = 0$, this expression loses not only mathematical sense but also indicates that the power is a limit value of the generated energy in the cross-sectional area of the space with respect not only to time but also x.

It can be shown that in the cross-sectional area of the cylinder through which the flow of energy enters the material carrier which moves with the speed of ϑ, energy derivatives with respect to time and x are bound by the expression:

$$Q_t^{'} = \vartheta \cdot Q_x^{'} \qquad (30)$$

This expression is suitable for answering the question, what speed is acceptable for power transmission over a distance. It can definitely be said that the velocity of the electromagnetic carrier is unconditionally preferred compared to the speed of any material carrier, because the derivative with respect to x (i.e. losses) is reduced in relation to $Q_t^{'}$ inversely to the speed.

With regard to energy, the transformation of the expression (30) into

$$Q_t^{'} \cdot dt = Q_x^{'} \cdot dx \qquad (31)$$

indicates that the equality of definite integrals of the left and right part presupposes limits on t and x with respect to x bound by a certain relationship dx/dt. This is not the speed of a carrier but the velocity of the environment which is more conveniently represented as finite increments $\Delta x/\Delta t$. For a cylinder, Δx means the boundaries of volume in which the absorbed power (energy per time unit) equals the difference between power capacities at the volume boundaries. If this difference does not change over time, the energy in the volume will grow over time proportionally to the difference. The general expression $P = f(x)$ implies that with as x increases the value P is decreasing, i.e. the value of P_{0i} will decrease for every subsequent interval Δx_i. Since the absorption of P_i is proportional to P_0, this value (i.e. P_i) will decrease. Thus, in every volume which corresponds to the interval Δx_i in a stationary environment, the rate of accumulation of energy will be different and will decrease from the cross-section to which the power is supplied. For an energy technological process, a technological requirement must be formulated in the form of specific (by volume or weight) amount of energy required to produce the expected result. Without calculation, it is clear that for a stationary environment, the requirement of energy equality in every interval Δx_i will be met at different time intervals in different i volume intervals. Only the movement of the environment along the power gradient combines the change of both energy derivatives, and the speed of the movement can be adjusted in such a way that it will provide necessary energy value in every volume interval upon its passing all the way which equal to the length of complete absorption of the flow [3].

III. Conclusion

The specificity of the analysed energy processes in the elements of ECS lies not only in their mathematical models. It can be agreed that the model in a form of expression (23) based on the assumption of linearity of the relative (to P_0) reduction of the second energy derivative $\left(P_x^{'} = a \cdot P_O\right)$ can be applied both to the transmission elements and the ETP.

In the physical sense, the difference lies in the fact that the energy in the elements of transmissions creates losses (they should be reduced in relation to the transmitted energy) whereas in the ETP, energy creates a result (the amount of absorbed energy should substantially exceed the amount of energy transmitted through the ETP). This difference can be called an inversion of efficiency, and it (the inversion produced in the ETP) must be regarded as a sign of consumer system which is distinctive from the systems of energy generation and transmission.

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