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DETERMINATION OF EFFICIENCY IN THE DESIGN PHASE OF THE ENTERPRISE BY THE METHOD OF FINITE RELATIONS

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ABSTRACT. The algorithm for estimating engineering solutions at the design stage in terms of the relative energy intensity by the method of finite relations (MFR) has been considered. The description and diagram of an energy consumption system serving as the base object in the analysis of energy efficiency for the manufacturing of products have been given. The basic features of using the method of finite relations at the design stage have been investigated. Based on energy estimation, the usefulness of the integrated approach to design for improving the energy efficiency of industrial enterprises has been proved. The aim of this paper is to describe the current approaches to solving energy-saving issues arising at the enterprise design stage to substantiate the possibility of using MFR to optimize design solutions in terms of energy efficiency. To achieve the aim set at the beginning of the paper, we consider an example from the book 'Industrial pumping systems' (Stasinopoulos *et al.,* 2012, p. 165) with the basic formulas and design values preserved. The main design tasks are to select the pump power P and determine the diameter of the pipeline D. The analysis of the given design solutions with the help of the MFR has clearly demonstrated the significant advantages of the integrated design approach over the traditional one. As a result, the use of the integrated approach to design made it possible to reduce the consumed design energy by 88% and the relative energy intensity $Q^{P}e_{(project)}$ from 10.468 to 1.215.

Introduction

As shown by long-term experience of research and practical work on industrial energy saving, the goal of improving energy efficiency cannot be achieved with standard solutions only (for example, replacing incandescent lamps with LEDs). It was established that the entire consumer energy system (CES) should be subject to management (Karpov *et al.,* 2012), the main energy efficiency indicator of which is the energy intensity of products, easily convertible into relative energy and currency indicators for any scale of production (from an individual enterprise to the country's GDP) (Chiaroni *et al.,* 2017; Hazi, Hazi, 2017; Locmelis *et al.,* 2017).

The statutory requirement to increase energy efficiency requires not only a critical analysis of all stages of the life cycle in terms of energy efficiency but also the development of new synthesis methods meeting the requirement of reducing energy consumption and serve as the development of equipment selection methods.

The concepts of energy management, energy audit, and targeted energy monitoring have appeared (Chin, Lin, 2015; Javied *et al.,* 2015; Thiede *at al*., 2012; Zheng *et al.,* 2018). The measures taken have yielded significant results. The integrated approach in design practice is considered as a key strategy to achieve the economic efficiency of technical systems and reduce their negative impact on the environment (Stasinopoulos *et al.,* 2012, p. 32).

The detailing of best practices in designing effective technical systems is in the book 'Designing Systems as a Whole. An Integrated Approach to Sustainable Engineering' by Australian scientists (Stansinoupolos *et al*., 2012). It should be noted that this book describes the accumulated design and engineering experience that allows you to create environmentally friendly and economical systems ensuring sustainable development, but there is no generalising method for assessing the energy efficiency of the proposed design solutions, which complicates the application of the described techniques for practical energy saving.

Materials and methods

The engineering consumer energy system (CES) is developed on the basis of equipment layout supplemented with energy-technological processes (ETP) provided by the production technology (Karpov *et al.,* 2012; Chiaroni *et al.,* 2017). The CES diagram is shown in Figure 1.

This diagram includes all the energy equipment of the enterprises but distributed along lines formed by continuous unidirectional flows of energy used in the energy technology process (ETP). The whole set of ETPs of the enterprise is divided into three types: ETP1 – the main one that manufactures products, ETP2 – auxiliary, ETP3 – providing living conditions. It is important that the energy process in each ETP create a numerically measurable result necessary to obtain products. Thus, the CES is not a formal combination of elements but a set of processes united by one goal – production. Naturally, only targeted management of the energy processes in the entire consumer system will reduce the value of the general production criterion of efficiency – the energy intensity of products. As the total number of results of the analysed processes also includes products manufactured by the enterprise, the CES should be considered the main and initial object in the hierarchy of production associations in systematic analyses of energy efficiency according to the criterion of energy intensity of products.

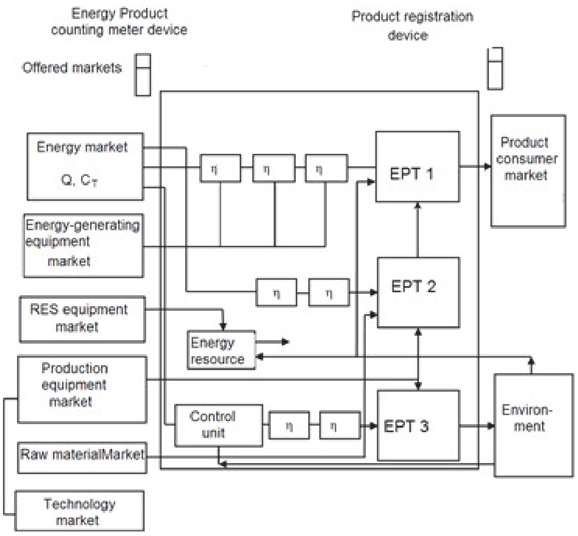

Figure 1. Diagram of the consumer energy system

The inclusion of ETPs in the diagram and analysis of energy efficiency should not be considered as the addition to some basic but rather as the creation of an analytical base for assessing systemic energy consumption, as all ETPs are subordinate to the technology of output. The type of energy is known for each ETP result. A comparison of the types needed to obtain results and a set of types of energy consumed determines the number of converters in a CES. However, the most important advantage of including ETPs in the CES diagram is that scientific indicators are introduced into the analysis that directly or indirectly determines the theoretical specific (per unit of the process result) energy consumption Qsp. Thus, the method of finite relations (MFR) received a scientific basis in the form of specific indicators and became the main method of analysis of the energy efficiency of consumer energy systems (Karpov, Yuldashev, 2010). The development of methods for using MFRs for specific ETPs, R results and energy lines is an objective of scientific research, the synthesis of which will create a theory of energy efficiency.

To achieve the aim set at the beginning of the paper, we consider an example from the book 'Industrial pumping systems' (Stasinopoulos *et al.,* 2012, p. 165) with the basic formulas and design values preserved, and then, by using the energy efficiency indicators adopted by the MFR, we will assess the design solutions made.

Features of application of the method of finite relations for the assessment of design solutions. To conduct an energy assessment of design solutions, it is proposed to use the MFR (Karpov, Yuldashev, 2010). The capabilities of this method were confirmed in laboratory and industrial conditions when determining the actual energy efficiency indicators of existing equipment (Karpov, 2014); however, an example of the assessment and optimisation of design solutions is presented for the first time.

It is generally accepted in the MFR that a technological process consumes energy to take any action leading to the desired result R. Therefore, to assess the energy efficiency of a result obtained in an energy-technological process, it is necessary, according to well-known scientifically based indicators, to establish the specific energy consumption Q^{SP} (per unit of result) (Karpov, Yuldashev, 2010). Multiplication of specific energy consumption Q^{SP} on the quantitative value of a given result R determines the minimum energy consumption Q_{theor} (excluding losses):

$$Q_{theor} = Q^{SP} R \tag{1}$$

Differentiation of identity (1) with respect to time t gives the following expression:

$$P_{theor} = P^{SP} R \tag{2}$$

It should be noted that in the case under consideration, the value of the result R is differential, as the target volumetric flow rate is set in the condition in the form of a constant value. The ratio $P_{theor}R^{-1} = P^{SP} = const$ and, therefore, $P_{theor}\ (P^{SP}\ R)^{-1} = 1$ represents the absolute energy intensity R and the relative energy intensity of the process, which for theoretical conditions (no energy loss) is 1. The indicated parameter values $Qtheor$, P_{theor} are minimal, as, at lower values, the target functioning of the ETP will cease, that is, the output of the *R* result will cease. A similar approach to the consideration of the technological process makes the task of energy saving optimisation, the solution of which is not to reduce energy consumption, but to provide a certain, scientifically-based minimum energy intensity for obtaining the result (production).

In this example, the theoretical value of power, ensuring the achievement of the given result of the action of the pumping system (volumetric flow rate at the outlet of the tap *W*), is determined according to the expression (3)

$$P_{theor} = P^{SP} \times W \tag{3}$$

The specific power required for the implementation of the process under consideration can be determined on the basis of a given pressure of the liquid *H*, its density *ρ* and gravitational acceleration *g*.

Then, using the formula (3), we obtain the numerical value of power:

$$P^{SP} = pgH \tag{4}$$

$$P_{theor} = 998.2 \times 9.81 \times 10 \times 0.001 = 97.92 \text{ W}.$$

The value of the power P_{theor} is the minimum necessary and objective for the implementation of the target functioning of the ETP, and at the same time, it does not depend on the level of engineering, the design of the system, or the power and technical equipment.

According to the MFR, the ratio of the estimated power of the installation $P_{project}$ to the theoretical P_{theor} is a value characterising the relative energy intensity of the ETP. This indicator is proposed to be called the relative energy intensity according to the project data $Q^{P}e_{(project)}$ and used in the future when assessing engineering solutions:

$$Q^{P}{}_{e(project)} = \frac{P_{project}}{P_{theor}}, \tag{5}$$

where $Q^{P}_{e(project)} < +\infty$

Thus, $Q^{P}e_{(project)}$ can play the role of an optimisation criterion that is numerically determined and is the basis for energy assessments of solutions made in the design process.

Results and discussion

1. Implementation example.

The main design tasks are to select the pump power *P* and determine the diameter of the pipeline *D*, which implement the technological process of pumping water from tank A to the tap, subject to the following technological requirements: temperature of the pumped liquid is 20 °C, target volumetric flow rate at the outlet is $W = 0.001$ m^{3}s^{-1}.

2. The general solution for the project task.

The energy balance of the flow between point 1 and point 2 (Figure 2) for this system is defined in general terms by the Bernoulli equation:

$$\frac{p_1}{\rho g} + \frac{\alpha_1 V_1^2}{2g} + z_1 + \sum \frac{P_i}{\rho g A_i V_i} = \frac{p_2}{\rho g} + \frac{\alpha_2 V_2^2}{2g} + z_2 + \sum f_i \left(\frac{L_i}{D_i}\right)\left(\frac{V_i^2}{2g}\right) + \sum K_{Li} \frac{V_i^2}{2g}, \tag{6}$$

where: *p* – pressure, Pa; *ρ* – density of the liquid, kgm^{-3}; *g* – acceleration of gravity, ms^{-2} ; *α* – the Coriolis correction factor; *V* – the average speed, ms^{-1} ; *z* – the height, m; *h* – the loss of fluid pressure, m; *f* – the coefficient of friction; *L* – the length of the pipeline, m; *D* – the diameter of the pipeline, m; KL – the pressure loss coefficient; *P* – pump power, W.

Considering the configuration of this system, several simplifications and substitutions can be made: $p_1 = p_2 = 0$ (atmospheric pressure), $V_1 = 0; z_1 = 0$.

As the outlet from reservoir A has a perfectly round shape, it may be that the corresponding partial losses can be neglected. The diameter of the pipeline along the entire length has the same value of *D*; therefore, the cross-sectional area along the entire length of the pipeline is equal to cross-sectional area of tank A and the average fluid flow rate at the pump outlet is constant and equal to V_2.

Suppose that the water pressure loss at the pump fittings, the tap fittings, and at the outlet of the tank A is negligible; therefore, the energy balance equation (6) can be converted into the following form:

$$\frac{P}{\rho g A V_2} = \frac{\alpha_2 V_2^2}{2g} + z_2 + f\left(\frac{L}{D}\right)\left(\frac{V_2^2}{2g}\right) + \sum K_{Li} \frac{V_2^2}{2g} \tag{7}$$

Parameter V_2 can be excluded from the energy balance equation by replacing it with a function of *W* and *D* by using the equation:

$$V_2 = \frac{W}{A} = \frac{4W}{\pi D^2} \tag{8}$$

Using the necessary transformations, we obtain the following formula for determining the pump power for this version of the system:

$$P = \left(\frac{8\rho W^3}{\pi^2 D^4}\right)\left[\alpha_2 + f\left(\frac{L}{D}\right) + \sum K_{Li}\right] + \rho g W_{z2} \tag{9}$$

The friction coefficient *f* also depends on the Reynolds number *Re*, which is determined from the expression:

$$Re = \frac{\rho V_2 D}{\mu}, \tag{10}$$

where: *μ* – dynamic viscosity of the liquid, Nsmm^{-2}

Substituting the expression value (8) into expression (10), we obtain:

$$Re = \frac{4\rho W}{\pi D \mu} \tag{11}$$

For a turbulent flow (Re > 4,000), to determine the parameter f, it is necessary to know the roughness equivalent of the inner surface of the pipeline ε, which is the known physical characteristic of the pipeline.

Thus, the relationship between the power of the pump P and the diameter of the pipeline D is determined by using known variable parameters of the system.

3. Engineering with the traditional approach to system design.

Let us make a selection of equipment (pipes and a pump of suitable capacity P) which shows a typical solution for any system with one pump and one pipeline for the pumping system. Based on the tabulated values for water at a temperature of 20 °C, density ρ = 998.2 kgm^{-3}, dynamic viscosity μ = 1.002 10^{-3} Nsm^{-2}. Configuration scheme is shown in Figure 2.

Calculate the Reynolds number using expression (10):

$$Re = \frac{4 \cdot 998.2 \cdot 0.001}{3.14 \cdot 1.002 \cdot 10^{-3} \cdot D} \tag{12}$$

The flow will be turbulent (Re > 4,000) at D < 0.317 m. The pipe diameter D = 0.317 m significantly exceeds the values acceptable for the system shown in Figure 1; therefore, without any risk, it can be assumed that the flow is turbulent. As the turbulent velocity profile is almost uniform along the entire length of the pipeline, we assume that $\alpha_1 = \alpha_2 = 1$.

For 90° threaded choke valves, the pressure loss coefficient will be:

$$K_{L4} = K_{L5} = K_{L6} = K_{L7} = 1.5.$$

For a fully open ball valve K_{LB} = 10 and the tap K_{LT} = 2.

After substitution of all known quantities, the equation of energy power (9) will take the form:

$$P = \left(\frac{8 \cdot 998.2 \cdot 0.001^3}{\pi^2 D^4}\right)\left[1 + f\left(\frac{30}{D}\right) + (1.5 \cdot 4 + 10 + 2)\right]$$
$$+ 008.2 \cdot 9.81 \cdot 0.001 \cdot 10$$
$$P = \left(\frac{8.0911 \cdot 10^{-7}}{D^4}\right)\left[f\left(\frac{30}{D}\right) + 19\right] + 97.923$$

Suppose that drawn copper pipes with a diameter of D = 0.015 m are used to manufacture the pipeline. We substitute this value into equation (12) to calculate the Reynolds number:

$$Re = \frac{1268.411}{0.015} = 84561.0$$

For drawn pipes, the roughness equivalent is ε = 0.0015 mm, thus

$$\frac{\varepsilon}{D} = \frac{0.0015}{15}$$

The friction coefficient f = 0.0195 at Re = 84561 and ε/D = 0.0001, therefore:

$$P = \left(\frac{8.0911 \cdot 10^{-7}}{0.015^4}\right)\left[0.0195\left(\frac{30}{0.015}\right) + 19\right] + 97.923 = 1025W$$

Thus, if in the system shown in Figure 1, drawn copper pipes with the diameter of D = 0.015 m are used, then to ensure a volumetric flow rate at the outlet W = 0.001 m^{3}s^{-1}, a pump with a power of P = 1,025 W is required.

The energy efficiency indicator of the engineering solution in a traditional design with the expression (5) will be:

$$Q^P_{e(project)} = \frac{1025}{97.92} = 10.468$$

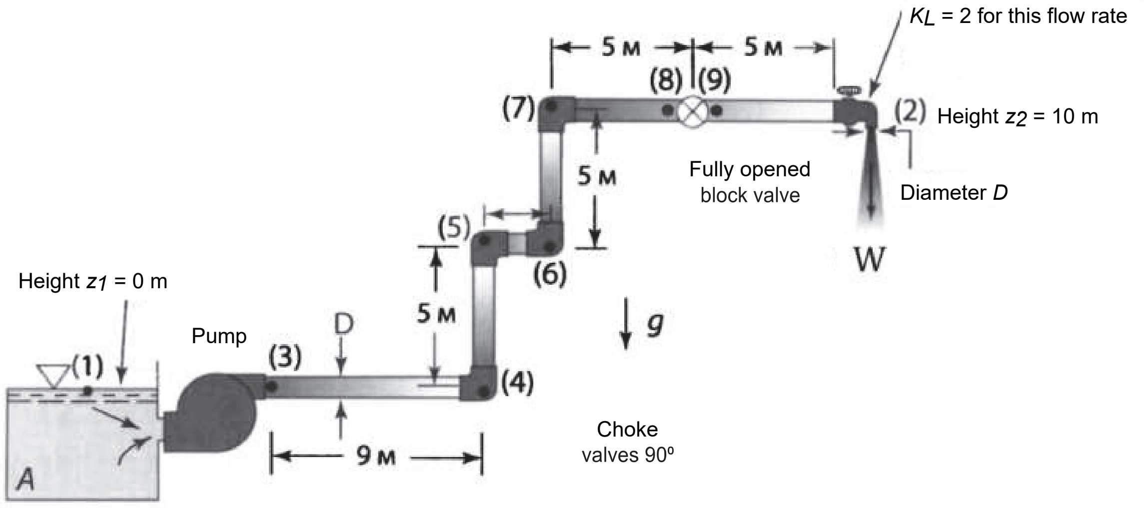

Figure 2. The typical configuration of the system

Based on the obtained value of design efficiency, we can conclude that this system has great potential in the field of energy conservation and should be optimised.

Integrated (complex approach) is the process of designing systems as a whole, during which the interrelations between subsystems and systems are actively considered, and solutions are sought in such a way that the same solution eliminates several problems at once (Stasinopoulos *et al.,* 2012, p. 35). Based on this definition, the main disadvantages of engineering solutions were formulated with the traditional design approach:

- The pipeline configuration assumes the loss of water pressure, which could have been avoided (the pipeline configuration was chosen taking into account the layout of the equipment and the window, but is not optimal from the point of view of efficiency);
- During the procedure for choosing the pipe diameter D and pump power P, the system was not considered as a whole (no connection was established between these indicators);
- Based on the foregoing reasons, the design process is complemented by two stages, which are carried out to improve the system and are designed to ensure its maximum efficiency;

- The pipeline configuration assumes the loss of water pressure, which could have been avoided (the pipeline configuration was chosen taking into account the layout of the equipment and the window, but is not optimal from the point of view of efficiency);
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  Based on the foregoing reasons, the design process is complemented by two stages, which are carried out to improve the system and are designed to ensure its maximum efficiency.

Stage 1: Design optimization (reduction of pressure losses)

At this stage, changes are made to the pipeline design taking into account the equipment layout and allowing you to reduce the pressure loss (Figure 3).

As the conditions for point 1 and point 2 in Figure 3 are the same as in Figure 2, and by using one pipeline and one pump, the energy balance equation described by expression (7) is applicable.

For threaded choke valves 45°: $K_{L4} = K_{L5} = 0.4$; for the fully open block valve $K_{L3} = 0.15$; the tap $K_{LT} = 2$.

The energy balance equation takes the form

$$P = \left(\frac{8.0911 \cdot 10^{-7}}{D^4}\right)\left[f\left(\frac{24}{D}\right) + 3.95\right] + 97.923$$

Suppose that in this case the same drawn copper pipes with the diameter of D = 0.015 m were selected. Substitute this value in equation (10) to calculate the Reynolds number:

$$Re = \frac{1268.411}{0.015} = 84561$$

For drawn pipes, ε = 0.0015 mm, thus:

$$\frac{\varepsilon}{D} = \frac{0.0015}{15} = 0.0001$$

The friction coefficient f = 0.0195 at Re = 84561 and εD^{-1} = 0.0001, therefore:

$$P = \left(\frac{8.9011 \cdot 10^{-7}}{0.015^4}\right)\left[0.0215\left(\frac{24}{0.015}\right) + 3.95\right] + 97.923 = 660W.$$

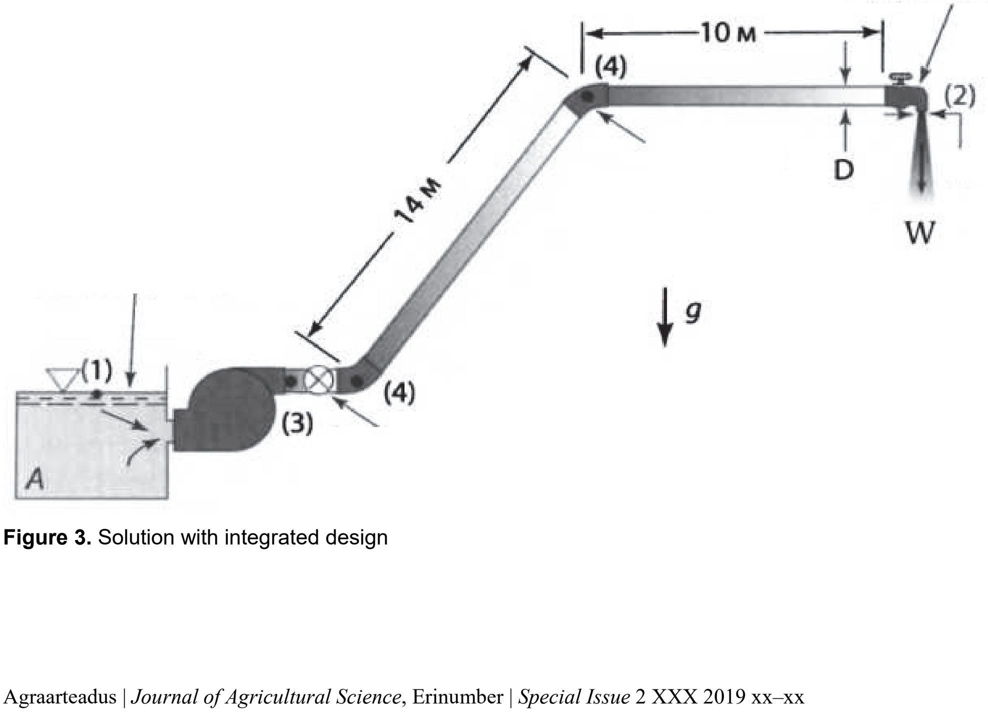

Figure 3. Solution with integrated design

Thus, if in the system shown in Fig.3, drawn copper pipes with the diameter of $D = 0.015$ m are used, then to ensure the volumetric flow rate at the outlet $W = 0.001$ m^{3}s^{-1}, a pump with a power of $P = 660$ W is required.

The energy efficiency indicator of the engineering solution at the first stage of improving the system according to the principles of the integrated approach to design according to expression (5) will be:

$$Q^P_{e(project)} = \frac{660}{97.92} = 6.740$$

In stage 1, the pipeline design was optimised, leading to a number of system improvements. With the diameter of the pipeline (D = 0.015 m), which was chosen with traditional design, the solution obtained with integrated design provides a 64% decrease in a design capacity and a decrease in the relative energy consumption according to the project $Q^Pe_{(project)}$ from 10.467 to 6,740.

Stage 2: Pump power optimization

At this stage, comprehensive optimisation of the diameter of the pipeline D and the power of the pump P is carried out. According to the equation (9), an increase in the diameter of D leads to a sharp decrease in the required power P. Combinations of the values of the pipe diameter and the power of the pump (with a step of increasing the diameter of 0.005 m) suitable for the system (Fig.3) are calculated in a similar way. The calculation results, as well as the total capital costs, are given by the authors of the working example and these were not additionally verified; however, for each proposed option, an energy assessment was carried out for the indicator $Q^Pe_{(project)}$ (Table 1).

Table 1. Calculation of pump power for a number of pipe diameters

Option number	D, m	Re	f	P, W	Capital costs, €	$Q^Pe_{(project)}$
1	0.015	84 561	0.0195	660	861	6,740
2	0.020	63 421	0.0205	242	966	2,471
3	0.025	50 736	0.0210	148	1,040	1,511
4	0.030	42 280	0.0215	119	1,118	1,215
5	0.040	31 710	0.0230	104	1,308	1,062

According to the data obtained, the dependences of the relative energy intensity are constructed for the project $Q^Pe_{(project)}$ and total capital costs for the respective optimisation options (Figure 4).

The analysis of data given in Figure 4 allows us to conclude that after the value of D = 0.03 m (option No. 4), a further increase in diameter does not allow a significant decrease in the relative energy intensity according to the project data $Q^Pe_{(project)}$, but it increases the cost of the system. Based on the foregoing, the final option for the selection of equipment becomes option No. 4 (Table 1). At Stage 2, the choice of pipeline diameter and pump power was optimised in terms of energy efficiency and costs. Note that the result of the second stage was a further decrease in power consumption by 82% and a decrease in relative energy intensity according to the project $Q^Pe_{(project)}$ from 6,740 to 1,215.

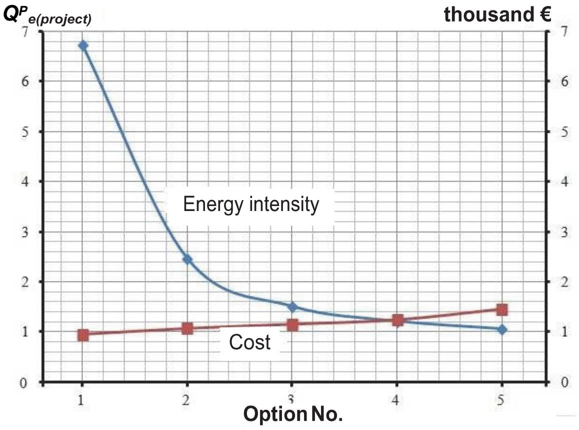

Figure 4. Graphs of the relative energy intensity according to the project data $Q^Pe_{(project)}$ and total capital costs for various options

4. Comparison of system characteristics

Parallel comparisons of the characteristics of systems with traditional and integrated design (Table 2) indicate significantly different results, which each of these approaches leads to. The costs per life cycle of the system, set out in the literature (Thiede *et al.,* 2012; Novak, 2014), with the integrated approach to design are five times lower than with the traditional one. Achieving this result was made possible due to a tenfold reduction in the energy intensity of the process.

Table 2. Comparison of the design results of two solutions

Solution	D, m	P, W	Total capital costs,€	Operational costs, €/month	Costs during life cycle – NPV, €	$Q^Pe_{(project)}$
Traditional design	0.015	1,025	1,303	55.5	13,582	10,468
Integrated approach	0.030	119	1,118	8	2,795	1,215

Conclusion

The introduced additional indicator of energy efficiency – relative (dimensionless) energy intensity of the process according to the project data $Q^Pe_{(project)}$ made it possible to evaluate the energy efficiency of the process at the design stage with the help of the MFR. This circumstance opens up the possibility of conducting an element-by-stage analysis of the system, developing a strategy for managing a common system indicator – product energy intensity.

To achieve the highest possible energy efficiency indicators of the enterprise's technical system, it is necessary to optimise the energy indicators of an enterprise at the stage of its creation and design study. Naturally, the main source of reducing operating costs throughout the entire life cycle of the system is to ensure the highest efficiency at the design stage. As practical experience shows, energy-saving measures implemented during operation have less impact on the energy intensity of products and are costly. Thus, it is proposed to start increasing energy efficiency in the sector by analysing the energy part of the enterprise's project. Elimination of imperfect engineering at the initial stage allows realising a significant potential for energy saving before the operation, avoiding the cost of eliminating design errors.

The analysis of the given design solutions with the help of the MFR has clearly demonstrated the significant advantages of the integrated design approach over the traditional one; therefore, this approach will be used in further studies on improving energy efficiency at agricultural enterprises. As a result, the use of the integrated approach to design made it possible to reduce the consumed design energy by 88% and the relative energy intensity $Q^{P}e_{(project)}$ from proportional units 10.468 to 1.215.

The algorithm proposed in the paper allows the use of the MFR to evaluate the examples of design decisions discussed in the book by the relative energy intensity index $Q^{P}e_{(project)}$ and to select the most optimal solution from the energy efficiency aspect. The decrease in the design power in the considered example became possible due to the inclusion of two additional steps in the design process and the selection of system implementation options based on the energy efficiency indicator.

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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;
AN – writing the manuscript, sampling analysis;
TK – editing and approval final manuscript, idea development;
AA – editing and approval final manuscript, design;
AA – editing and approval final manuscript, design.

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