energies

Article

# Energy Efficiency Indicator of Pumping Equipment Usage

Oleksandr Ivchenko [1], Vladyslav Andrusiak [1], Vladyslav Kondus [1], Ivan Pavlenko [1], Serhii Petrenko [1], Andżelika Krupińska [2], Sylwia Włodarczak [2], Magdalena Matuszak [2] and Marek Ochowiak [2,*]

[1] Faculty of Technical Systems and Energy Efficient Technologies, Sumy State University, 2, Rymskogo-Korsakova St., 40007 Sumy, Ukraine; s.petrenko@pgm.sumdu.edu.ua (S.P.)
[2] Department of Chemical Engineering and Equipment, Poznan University of Technology, 60-965 Poznan, Poland; andzelika.krupinska@put.poznan.pl (A.K.)
* Correspondence: marek.ochowiak@put.poznan.pl

**Abstract:** The rational choice of pumping units and the effective usage of the corresponding pumping equipment are urgent problems in terms of ensuring the energy efficiency of up-to-date enterprises. The research aims to develop an energy efficiency indicator for torque flow pump usage to improve the decision-making procedure for choosing the corresponding pumping equipment for specific production conditions. Based on a study of the requirements of international standards for energy efficiency, a methodology for evaluating torque flow pumps according to the energy efficiency indicators is proposed, as the ratio between the values of the average compensated network power and the reference pump inlet power can determine the degree of reduced energy equipment operation efficiency in terms of the energy efficiency of pumping liquids. It was proposed to apply the base point method to determine the so-called compromise point of energy consumption for liquid pumping. This is a point for which another point, by the Pareto compromise, is likely to have a more significant (worse) value for energy consumption than the rest of the set of possible values.

**Keywords:** energy efficiency; torque flow parameter evaluation; process innovation; power network; pump selection; decision-making algorithm



**Citation:** Ivchenko, O.; Andrusiak, V.; Kondus, V.; Pavlenko, I.; Petrenko, S.; Krupińska, A.; Włodarczak, S.; Matuszak, M.; Ochowiak, M. Energy Efficiency Indicator of Pumping Equipment Usage. *Energies* **2023**, *16*, 5820. https://doi.org/10.3390/en16155820

Academic Editors: Levon Gevorkov, Emiliia Iakovleva, Irina Kirpichnikova, Vladimir Prakht and Anton Rassõlkin

Received: 12 June 2023
Revised: 26 July 2023
Accepted: 3 August 2023
Published: 5 August 2023



## 1. Introduction

Global industry cannot operate appropriately without energy-efficient pump usage in the industrial enterprises and organizations of the various economic and service sectors. According to experts, up to 10% of all world electricity is spent simply pumping liquid [1]. Nowadays, most pumps are used in such a way that a significant part of their service life is spent working in underload mode [2], which results in a decrease in the generalized energy efficiency indicator of their work due to the occurrence of various phenomena in the fluid flow, such as re-circulation [3].

The study of current trends in addressing the existing issues of increasing the energy efficiency levels for pumping equipment indicates quite radical steps are required regarding the regulation requirements for the energy efficiency indicators, particularly the introduction of the following:

- The energy efficiency of equipment usage for pumping water [4];
- Requirements for energy-related products (Directive 2009/125/EC of the European Parliament and of the Council establishing a framework for the setting of ecodesign requirements for energy-related products) in terms of implementing ecodesign requirements for water pumps [5];
- The (EC) 641/2009 Regulation, on implementing Directive 2005/32/EC of the European Parliament and of the Council on circulation pumps [6].

Based on the analysis of the (EU) 547/2012 Regulation [7], it was found that the efficiency of a hydraulic pump is measured by pressure head and flow corresponding to the best efficiency point (BEP), partial load (PL), and overload (OL) for a full impeller diameter $D_2$ using clean, cold water. The document contains a polynomial that describes the mathematical dependence for calculating the indicator of the required minimum efficiency at the BEP.

The energy efficiency is evaluated according to European Commission regulation No. 641/2009 of 22 July 2009 [6]. For this purpose, the energy efficiency index (EEI) is introduced. The methodology for its calculation is described in detail in Annex II of the above-mentioned regulation. Particularly, for glandless, self-contained circulation pumps, the EEI is calculated according to this document, and cannot exceed the value for this EEI by more than 0.2. It is calculated as a ratio of the weighted average power of the circulation pump $P_{L,avg}$ to the circulation pump reference power $P_{ref}$ at given values of pressure head $H$ and flow rate $Q$. Also, it considers the conversion factor, which ensures that when the conversion factor is determined, only 20% of the circulation pumps of a particular type have an EEI less than the set value.

According to the results of the requirements analysis of ISO 9906:2012 [8], it was found that indicators related to the pumps' energy efficiency in cases where they are manufacturer guaranteed should only be evaluated according to the values of efficiency $\eta$ and pump power $P$ using the "line from zero" method for determining dependencies $H(Q)$, $P(Q)$, and $\eta(Q)$.

After summarizing the requirements of the international standards on energy efficiency indicators for pumping equipment, the following conclusions were reached. Mainly, it was found that these documents implement measures to determine the critical energy characteristics of the pumping equipment. However, this make it possible to prevent products with low energy efficiency from entering the market.

Studies of the modern achievements by pumping equipment manufacturers, for example, torque flow pumps, which, due to their design differences, can be used in production processes in almost all economic sectors, highlighted the problem of choosing the most efficient pump, especially under periodic changes in its operating modes. The main advantages of these pumps compared to other types are durability and reliability [9,10]. Simultaneously, the main disadvantage is low energy efficiency. The efficiency factor $\eta$ of such pumps does not exceed 63% [11–13]. The pros and cons of these pumps are due to the specifics of their design and the combined workflow (energy transfer due to the vortex and force interaction of the flow with the impeller blades) [14,15].

The following state-of-the-art indicators of energy efficiency in pumping equipment usage were also considered before formulating the primary purpose of the research. Particularly, in 1998, Ejiri and Kubo [16] were among those who laid the foundations of the flow and loss analysis of higher-speed torque pumps. In 2015, Krishtop [17] proposed a general way to design the flow parts for energy-efficient torque flow pumps.

In 2023, Yang et al. [18] integrated a hydraulic pump and a motor into a single device for mutual energy conversion. As a result, multiparameter-controlled hydraulic equipment was proposed based on active energy regulation. Finally, Li et al. [19] developed a prediction model for the energy conversion characteristics of flow pumps during transient processes.

These studies substantiate the need for an effective energy efficiency indicator for pump usage. Such an indicator would enable the rational choice of pumping equipment for specific production conditions to be made.

Nowadays, for the convenience of assessing work performance during pump selection, most manufacturers suggest using the parametric series, which indicates the range of the pump's operation according to the dependence $H(Q)$, the size of the impeller diameter, or changes in its rotational speed.

Figure 1 shows a parametric range of torque flow pumps in the range of flow rate $Q$ from 2 $m^3/h$ to 600 $m^3/h$ and pressure head $H$ from 1 m to 60 m.

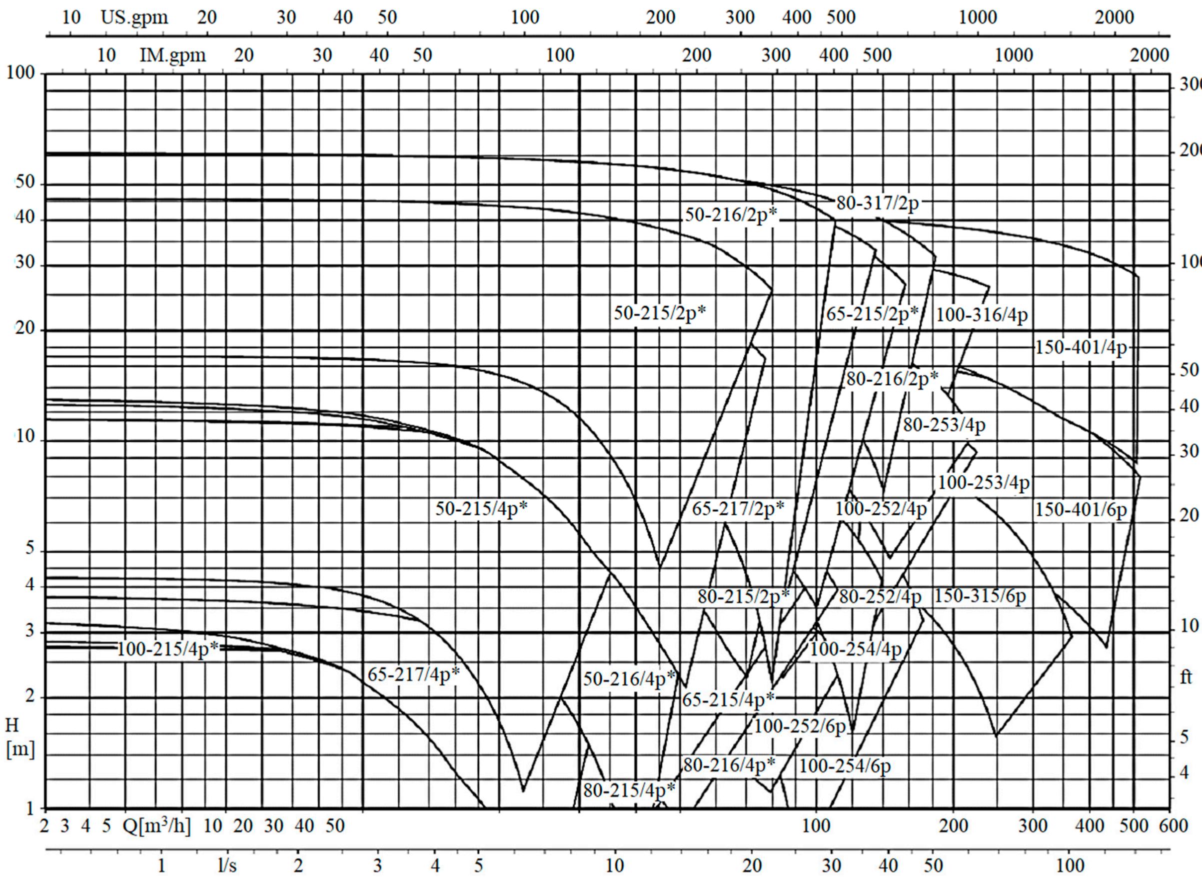


**Figure 1.** Parametric pump series [20]: *—trimmed impeller.

The traditional method of selecting pump equipment recommends calculating the value of efficiency $\eta_{NOM}$ at the nominal operation point $H(Q_{NOM})$. However, this approach usually does not coincide with the pump's designed operation mode $H(Q^{BEP})$. Therefore, it does not enable the choice of equipment with the maximum value of energy efficiency at this point.

For some networks, selecting a pump with a working point $Q = 100$ m$^3$/h and $H = 30$ m is necessary. According to Figure 1, these technical parameters can provide multiple pumps: 50–216/2p*, 60–215/2p*, 89–216/2p*, 80–317/2p*, and others. Simultaneously, this point is not a BEP for these pumps. Energy efficiency parameter determination is possible according to the dependence $\eta$ for each pump at the corresponding point. However, the equipment manufacturer provides this dependence for the values of the impellers' nominal diameters, which are manufactured without using the procedure for trimming them according to the specified parameters or considering the possibility of using frequency adjustment of the pump drive.

Decision-making on pump choice becomes more challenging when it provides technological parameters with different values of the dependence $H(Q)$ and considers the parameters of its energy-efficient operation from the time interval in each technological mode.

Thus, the solution to the scientific and technical problem of choosing energy-efficient pumping equipment is becoming relevant, in order to significantly improve energy consumption when pumping liquids.

Overall, the research aims to develop an energy efficiency indicator for torque flow pump usage to improve the decision-making procedure for choosing the corresponding pumping equipment for specific production conditions.

## 2. Materials and Methods

Based on analysis of the legislative acts [5–7] and the regulatory documents [21–23], to improve the decision-making procedure for the pumping equipment choice in specific production conditions, it is proposed to use a dimensionless value—an indicator of equipment energy efficiency ($I_{EEP}$), which is calculated by the expression:

$$I_{EEP} = 1 - \varepsilon, \tag{1}$$

where $\varepsilon$—the energy efficiency indicator for the pumping equipment usage.

The value $\varepsilon$ is proposed to be calculated according to the expression of Clause 6.2.9 of EN 16297-1 [21] to determine the energy efficiency indicator without consideration of the conversion factor $C_{xx\%}$:

$$\varepsilon = \frac{P_{L,avg}}{P_{ref}}, \tag{2}$$

where $P_{L,avg}$—the average compensated network power, W; $P_{ref}$—the reference power at the pump inlet, W.

The value $P_{L,avg}$ is calculated following the recommendations given in clause 6.2.8 of EN 16297-1 [21], but given that 100% addition of pumping equipment falls to a point, we characterized the operating value of the network under the equipment selection as:

$$P_{L,avg} = \sum_{i\%=1}^{N} L_{i\%} \cdot P_{L,i\%}, \tag{3}$$

where $P_{L,i\%}$—the network hydraulic power under the $i$-th loading mode W; $L_{i\%}$—the value of the operation period of pumping equipment in the $i$-th loading mode, determined in % of the total period of its operation according to the future load profile and to the curve $H_{fit}(Q)$:

$$H_{fit} = A \cdot Q^3 + B \cdot Q^2 + C \cdot Q + D, \tag{4}$$

where $A$, $B$, $C$, and $D$—coefficients of the approximating curve.

The corresponding curve is calculated using the following procedure:

(a) If the pump has more than one head and flow characteristic, then the calculation is performed on the maximum of them;
(b) At least 10 points are used, evenly distributed to fit the curve "$Q$-$H$";
(c) The function $H_{fit}(Q)$ for the corresponding pump is selected using the least squares method.

The network hydraulic power $P_{L,i\%}(Q_i)$ is calculated as follows:

$$P_{L,i\%}(Q) = 2.72 \cdot Q_i \cdot h_{net}\left(Q_i^{net}\right), \tag{5}$$

where 2.72—the coefficient of the pumped liquid density (for simplification, it is accepted for water flow density $\rho$ = 1000 kg/m$^3$) as a free fall coefficient and the dimension recalculation for delivered flow rate $Q$; $Q_i^{net}$—flow rate for the $i$-th network loading mode, m$^3$/h; $h_{net}$—a function that characterizes the network head rate, m:

$$h_{net}\left(Q_i^{net}\right) = a + k \cdot \left(Q_i^{net}\right)^2, \tag{6}$$

where $a$—the geodetic height of the network, m; $k$—network resistance coefficient, s$^2$/m$^5$.

The reference input power $P_{ref}$ is calculated by the following expressions:

$$P_{ref} = \frac{P_{hyd}(Q^*)}{\eta_{Q^*}}, \tag{7}$$

where $P_{hyd}$—the hydraulic output power, W; $\eta_{Q^*}$—efficiency of pumping equipment at the flow rate of pumping equipment $Q^*$, m$^3$/h, calculated based on the definition:

(1) The indicator of the required minimum efficiency at the point of optimum pump efficiency $(\eta_{BEP})_{\min}$ according to the requirements of the (EU) 547/2012 Regulation [7], implementing Directive 2009/125/EU [5] concerning requirements for pumps, designated as $Q^{BEP}$ [7];
(2) The EEI of glandless standalone circulators according to the requirements of EN 16297 series, designated as $Q^{EEI}$ [17–19].

The value of $Q^{BEP}$ is determined according to the catalogs of pumping equipment manufacturers for maximum efficiency. Then,

$$\eta_{Q^*} = \eta_{BEP}. \tag{8}$$

The value $Q^{EEI}$ is determined for the point of the curve $H_{fit}(Q)$, at which $P_{hyd}$ has the maximum value of the function $P_{hyd}(Q^*)$ by expression in the flow rate values range according to Clause 5.7.2 of the international standard ISO 9906:2012 [8]:

$$P_{hyd}(Q^*) = 2.72 \cdot Q^* \cdot H_{fit}(Q^*). \tag{9}$$

Then, the value $\eta_{Q^*}$ is determined for the point with the flow rate $Q^{EEI}$, and the following designation of this value is accepted:

$$\eta_{Q^*} = \eta_{EEI}. \tag{10}$$

This clause means the following: unless otherwise agreed, tests may be carried out at a rotational frequency in a range of 50–120% of the set rotational frequency for a given flow rate, head, and power. The efficiency changes can be ignored if the rotational frequency changes are within 20% of the set value.

## 3. Results

### 3.1. General Provisions for the Study

Experimental studies of the possibilities of the procedure for determining the EEI for the pumping equipment used while choosing it were carried out for actual pumps from two manufacturers, in particular, "KSB type Sewatec F" and "JSC Nasosenergomash Sumy" of the torque flow type.

The characteristics of the operating point of the conventional network are presented in Table 1.

**Table 1.** Technical characteristics of the conventional network.

| Characteristic of the Conventional Network | Value |
|---|---|
| Flow rate at the nominal network loading mode $Q_{NOM}$, $m^3/h$ | 100 |
| Maximum flow rate $Q_{max} = 1.2 \cdot Q_{NOM}$, $m^3/h$ | 120 |
| Pressure head at the nominal network loading mode $H_{NOM}$, m | 30 |
| The minimum head rate in the network $H_{min}$, m | 10 |
| The maximum head rate in the network $H_{max}$, m | 45 |

Figure 2 shows the results of the function $H_{fit}(Q)$ selection for the pumps (Table 2) according to the algorithm specified in the description of expression (4). The function $H_{fit}(Q)$ selection data are taken from the official sources [20,23] for each equipment manufacturer. The $R^2$ parameter determined the accuracy of the model. Particularly, for function $H_{fit}(Q)$ presented in Figure 2, its value varies in a range of $R^2$ = 0.9901–0.9993.

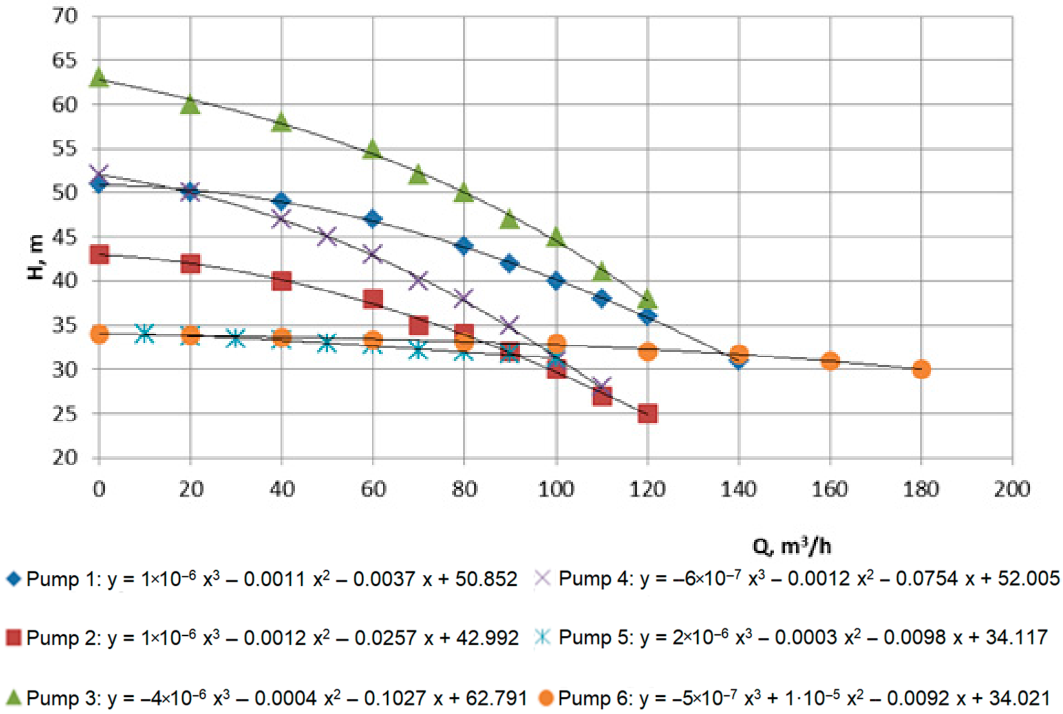


**Figure 2.** Function $H_{fit}(Q)$ selection results for pumps.

**Table 2.** Technical characteristics of pumps.

| Technical Characteristics | Pump Markings | | | | | |
|---|---|---|---|---|---|---|
| | **065–215 (210)** [1] | **065–215 (190)** [1] | **050–216 (210)** [1] | **050–216 (190)** [1] | **80–32** | **125–32** |
| Pump ID | 1 | 2 | 3 | 4 | 5 | 6 |
| Size $D_2$, mm | 210 | 190 | 210 | 190 | 325 | 325 |
| Rotation speed $n$, rpm | 2900 | 2900 | 2900 | 2900 | 1500 | 1500 |
| Head rate [2] $H_{NOM}$ at the point $Q_{NOM}$, m | 40.18 | 29.71 | 44.56 | 31.43 | 31.32 | 32.77 |
| Efficiency [3] $\eta_{NOM}$, % | 57.8 | 53.6 | 59.1 | 56.0 | 39.0 | 40.0 |

[1] The authors introduced these values to simplify the identification of the same pump types with different impeller diameters $D_2$. [2] The head rate $H_{NOM}$ is determined by the function $H_{fit}(Q)$ for each pump according to the data presented in Figure 2 for the flow rate $Q_{NOM}$. [3] The values of $\eta_{NOM}$ for each pump are taken from the official sources [16,19] for each equipment manufacturer for the flow rate of $Q_{NOM}$.

The conditional load profile of pumping equipment for calculating the average compensated network power is shown in Table 3.

**Table 3.** Loading profile of pumping equipment for calculating the average compensated power of the network.

| The Ratio of $Q/Q_{NOM}$, % | Value [1] of $h_{net}(Q)$, m | Operating Time per Year in Hours $L_{i\%}$, % |
|---|---|---|
| 120 | 38.8 | 10 |
| 100 | 30.0 | 60 |
| 70 | 19.8 | 10 |
| 50 | 15.0 | 10 |
| 20 | 10.8 | 10 |

[1] The $h_{net}(Q)$ value is calculated with expression (6) according to the network characteristics.

### 3.2. Calculation Results of Energy Efficiency Indicators for the Use of Pumping Equipment When Applying the Efficiency Indicator at the Point of Optimal Pump Efficiency $\eta_{BEP}$

The corresponding results of calculating the energy efficiency indicators of pumping equipment applying the efficiency indicator at the point of optimal pump efficiency $\eta_{BEP}$ are summarized in Table 4.

**Table 4.** Calculation results of energy efficiency indicators for pumping equipment using the efficiency indicator at the point of optimal pump efficiency.

| Indicator | Pump ID | | | | | | Notes |
|---|---|---|---|---|---|---|---|
| | Pump 1 | Pump 2 | Pump 3 | Pump 4 | Pump 5 | Pump 6 | |
| $Q^{BEP}$, m$^3$/h | 110 | 91 | 80 | 68 | 80 | 125 | Note 1 |
| $\eta_{BEP}$, % | 58.9 | 56.6 | 60.2 | 59.0 | 40.0 | 41.0 | Note 1 |
| $H^{BEP}$, $m$ | 38.11 | 31.68 | 50.01 | 40.93 | 31.97 | 32.16 | Note 2 |
| $P_{hyd}(Q^{BEP})$, W | 11,403.60 | 7841.11 | 10,882.42 | 7571.30 | 6956.83 | 10,934.24 | Equation (9) |
| $P_{ref}(Q^{BEP})$, W | 19,360.96 | 13,853.55 | 18,077.11 | 12,832.72 | 17,392.09 | 26,668.88 | Equation (7) |
| $P_{L,avg}$, W | 6802.18 | | | | | | Equation (3) |
| $P_{L,avg}^{NOM}$, W | 8160.00 | | | | | | Note 3 |
| $\varepsilon_{BEP}$ | 0.351 | 0.491 | 0.376 | 0.530 | 0.391 | 0.255 | Equation (2) |
| $\varepsilon_{BEP}^{NOM}$ | 0.421 | 0.589 | 0.451 | 0.636 | 0.469 | 0.306 | Note 3 |
| $I_{EEP_{BEP}}$ | 0.649 | 0.509 | 0.624 | 0.470 | 0.609 | 0.745 | Equation (1) |
| $I_{EEP_{BEP}}^{NOM}$ | 0.579 | 0.411 | 0.549 | 0.364 | 0.531 | 0.694 | Note 3 |

Note 1. The values of $Q^{BEP}$ and $\eta_{BEP}$ for each pump are taken from the official Internet resources of each equipment manufacturer [20,23]. Note 2. The value of $H^{BEP}$ is determined by the function $H_{fit}(Q)$ for each pump according to the data in Figure 2 for the flow rate at the point $Q^{BEP}$. Note 3. Values of the power $P_{L,avg}^{NOM}$, the energy efficiency indicator for the use of pumping equipment $\varepsilon_{BEP}^{NOM}$, and the energy efficiency indicator for the use of pumping equipment $I_{EEP_{BEP}}^{NOM}$ are determined for a point with flow $Q_{NOM}$ provided that the operating time of the pump at this point per year in hours is approximately equal to 100%, i.e., $L_{100\%}^{NOM} = 100$.

### 3.3. Calculation Results of Energy Efficiency Indicators for the Use of Pumping Equipment at the Maximum Value of the Function $P_{hyd}(Q^{EEI})$

The corresponding calculation results of the energy efficiency indicators for pumping equipment using the maximum value of the function $P_{hyd}(Q^{EEI})$ are presented in Table 5.

### 3.4. Diagram of the Energy Efficiency Indicators' Distribution

It is proposed to use the energy efficiency indicator of the pumping equipment use ($I_{EEI}$) to automate the decision-making for pumping equipment choice under its usage conditions by providing technological parameters of different dependence $H(Q)$ values and considering the energy-efficiency parameters.

Based on the results of the research, it was found that the ratio between the average compensated power values of the network $P_{L,avg,}$ and the reference power at the pump inlet $P_{ref}$ can determine the degree of the reduced equipment energy efficiency in terms of the energy efficiency of pumping liquid.

It was proposed to apply the base point method to determine the so-called compromise point of energy consumption for liquid pumping. This is such a point for which another point, per the Pareto compromise, has a greater (worse) energy consumption value than the rest of the set of possible values.

It was proposed to use the average compensated power of the network $P_{L,avg}$ as a "compromise point", which makes it possible to take into account on each network profile not only the values of the network losses parameters $h_{net}$ and the required flow rate $Q$

but also the operation of pumping equipment on each profile for the specified period of equipment operation.

Using Equation (1), the energy efficiency indicator calculation for the pumping equipment makes it possible to compare the energy efficiency of various pumps in a simplified form. It provides a decision on their energy efficiency based on the lowest value of this indicator. The diagram in Figure 3 is proposed as an example of actual pump selection.

**Table 5.** The calculation results of energy efficiency indicators for the use of pumping equipment at the maximum value of the function $P_{hyd}(Q^{EEI})$.

| Indicator [1] | Pump ID | | | | | | Notes |
|---|---|---|---|---|---|---|---|
| | Pump 1 | Pump 2 | Pump 3 | Pump 4 | Pump 5 | Pump 6 | |
| $Q^{EEI}$, m$^3$/h | 132.31 | 111.24 | 113.94 | 97.10 | 100.00 | 180.00 | Equation (7) [2] |
| $H^{EEI}$, m | 32.93 | 27.07 | 40.00 | 32.41 | 31.32 | 30.03 | Equation (7) [2] |
| $\eta_{EEI}$, % | 56.24 | 49.75 | 57.36 | 56.38 | 40.00 | 41.00 | Equation (9) |
| $P_{hyd}(Q^{EEI})$, W | 11,851.09 | 8190.84 | 12,398.43 | 8558.95 | 8519.69 | 14,702.86 | Equation (9) |
| $Pref(Q^{EEI})$, W | 21,072.36 | 16,464.0 | 21,615.12 | 15,180.82 | 21,299.22 | 35,860.63 | Equation (7) [2] |
| $P_{L,avg}$, W | 6810.88 | | | | | | Equation (3) |
| $P_{L,avg}^{NOM}$, W | 8160.00 | | | | | | Table 4 |
| $\varepsilon_{EEI}$ | 0.387 | 0.496 | 0.378 | 0.538 | 0.383 | 0.228 | Equation (2) |
| $\varepsilon_{EEI}^{NOM}$ | 0.323 | 0.414 | 0.315 | 0.449 | 0.320 | 0.190 | Note 1 |
| $I_{EEP_{EEI}}$ | 0.613 | 0.504 | 0.622 | 0.462 | 0.617 | 0.772 | Equation (1) |
| $I_{EEP_{EEI}}^{NOM}$ | 0.677 | 0.586 | 0.685 | 0.551 | 0.680 | 0.810 | Note 1 |

[1] Values of the energy efficiency indicator for the use of pumping equipment $\varepsilon_{EEI}^{NOM}$ and the energy efficiency indicator for the use of pumping equipment $I_{EEP_{EEI}}^{NOM}$ are determined for a point with flow $Q_{NOM}$ provided that the operating time of the pump at this point per year in hours is approximately equal to 100%, i.e., $L_{100\%}^{NOM} = 100$. [2] In this case, $\eta_{Q*}$—efficiency of pumping equipment at the BEP, $Q$—flow rate at BEP, and $H$—head at BEP.

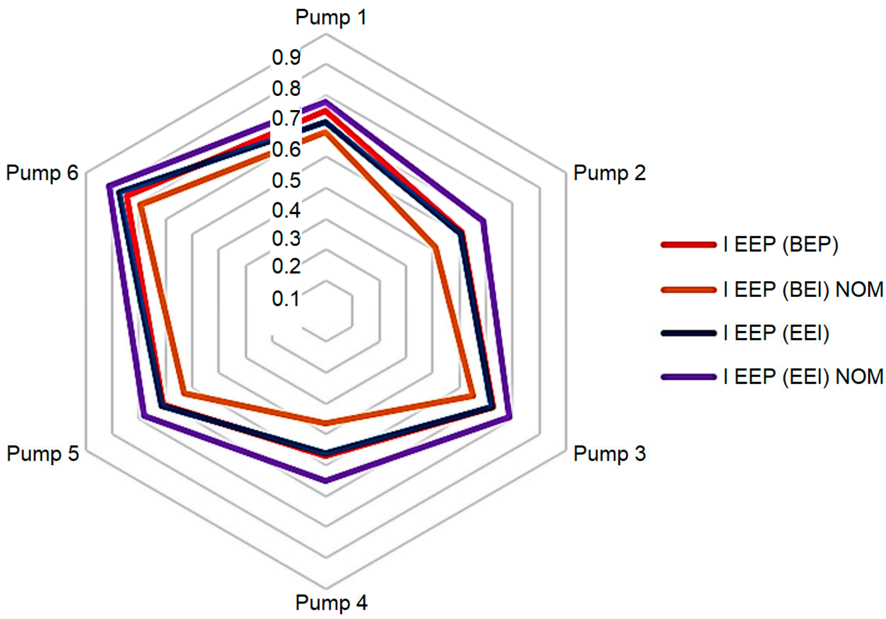


**Figure 3.** Diagram of the energy efficiency indicators distribution for the pump use according to Tables 4 and 5.

The paper also proposes a distribution diagram for the pump efficiency (Figure 4) to compare the energy performance of pumping equipment.

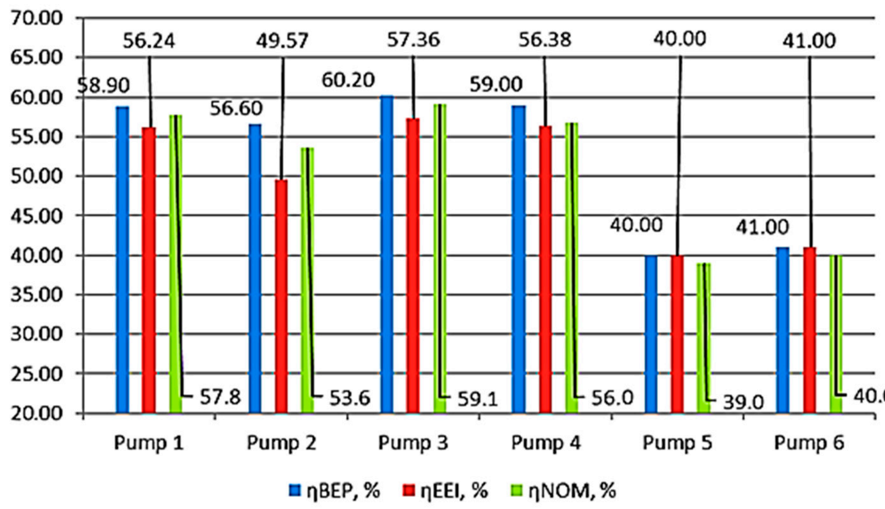


**Figure 4.** Pump efficiency distribution diagram.

Figure 4 shows the difference between the results of calculating the energy indicators of pumps (e.g., $\eta_{BEP}$, $\eta_{EEI}$) and proves that the implemented indicator $\eta_{EEI}$ more accurately reflects the pump's energy consumption. In turn, this proves the practical significance of the proposed work. As for the numbers in the columns, their presence helps to assess the results of the calculations more accurately.

The indicator $\eta_{nom}$ characterizes the efficiency of the pumping equipment in its operational mode at the nominal point of the network $Q_{NOM}$ = 100 m$^3$/h.

Respectively, it is proposed to rank the pumps for each energy efficiency indicator shown in Tables 4 and 5 for the subsequent analysis of the most efficient pumping equipment for given network load modes.

The results of the comparative analysis are summarized in Table 6 for various methods of evaluating the energy indicators of pumping equipment usage.

**Table 6.** Rating of pumps' efficiency.

| Indicator | Pump ID | | | | | |
|---|---|---|---|---|---|---|
| | Pump 1 | Pump 2 | Pump 3 | Pump 4 | Pump 5 | Pump 6 |
| $\eta_{EEI}$ | 3 | 4 | 1 | 2 | 6 | 5 |
| $\eta_{BEP}$ | 3 | 4 | 1 | 2 | 6 | 5 |
| $\eta_{NOM}$ | 2 | 4 | 1 | 3 | 5 | 6 |
| $I_{EEP_{EEI}}$ | 3 | 2 | 5 | 1 | 4 | 6 |
| $I_{EEP_{EEI}}^{NOM}$ | 3 | 2 | 3 | 1 | 4 | 6 |
| $I_{EEP_{BEP}}$ | 5 | 2 | 4 | 1 | 3 | 6 |
| $I_{EEP_{BEP}}^{NOM}$ | 5 | 2 | 4 | 1 | 3 | 6 |

Thus, the general algorithm for calculating the energy efficiency indicator value for the use of pumping equipment for specific operating conditions is presented in Figure 5.

The distribution diagram of the pump efficiency coefficients for the calculation of the energy efficiency indicator value for the pumping equipment used for specific operating conditions has some limitations:

Firstly, the calculations use the value of the constant liquid density $\rho$ = 1000 kg/m$^3$, which does not consider the possibility of operating two or more liquids with different densities, for example, a dairy product packaging line.

Secondly, restrictions are introduced regarding the constant characteristics of the geometric dimensions of the functional elements of pumping equipment and its shaft rotation frequency. This does not allow for adjustment of the pump operation for the corresponding modes, mainly by geometric shape (cutting the impeller) and frequency adjustment.

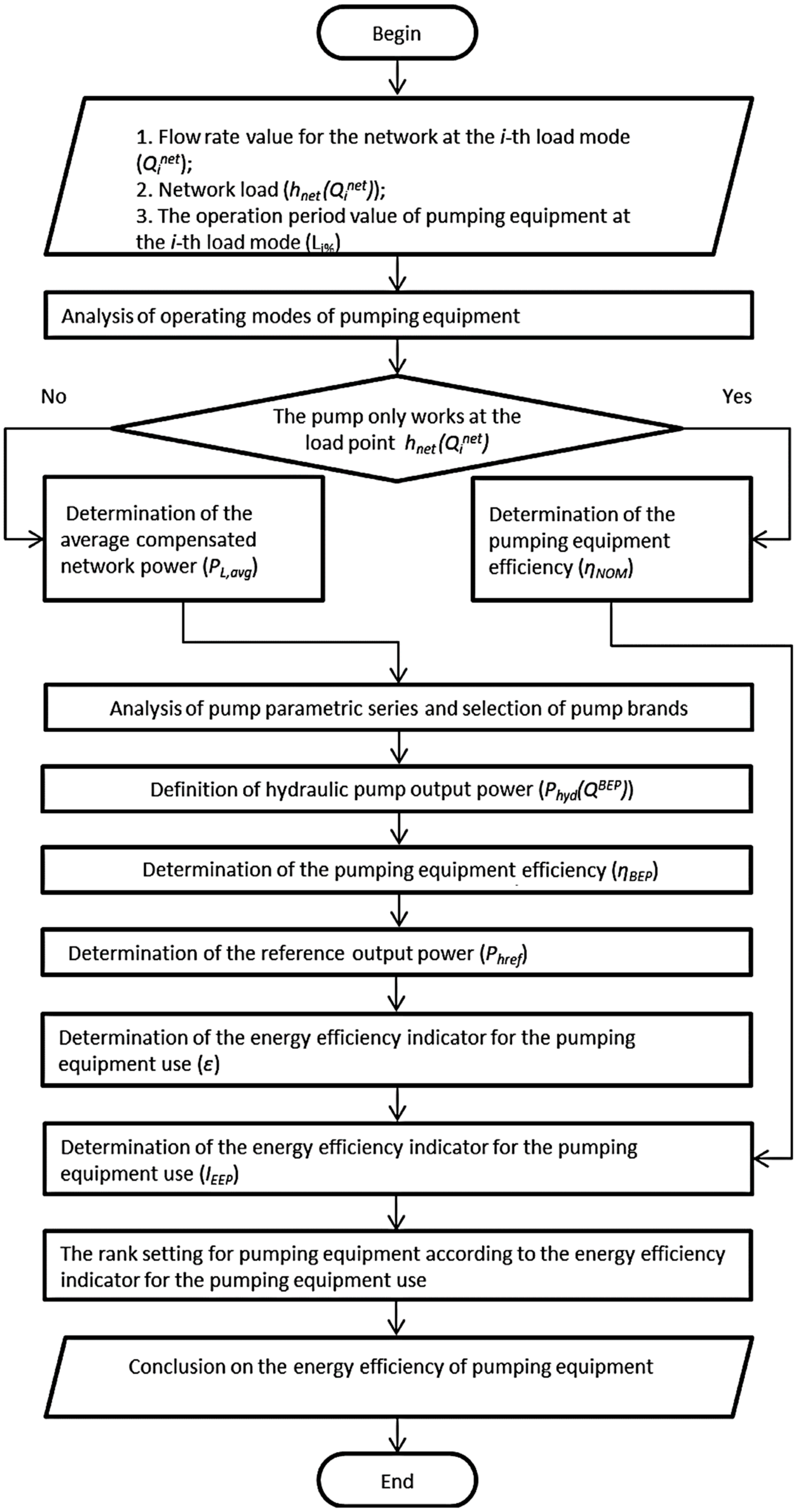


**Figure 5.** Algorithm for calculating the energy efficiency indicator value for using pumping equipment for specific operating conditions.

Thirdly, the energy consumption value only at a single point is considered. For a more efficient solution, it is advisable to consider the actual energy consumption of the pump during operation at each loading mode.

Finally, when the pumping equipment operates only on a single loading mode at point $H(Q_{NOM})$, the EEI of its usage is calculated as follows, $\varepsilon = \eta_{NOM}$.

## 4. Discussion

The results can be analyzed by comparing them with the traditional approach to pumping equipment selection based on the efficiency $\eta_{NOM}$ at the nominal point $H(Q_{NOM})$. Particularly, Table 6 shows that the most efficient pump for the given network load conditions in terms of pump energy efficiency indicators is Pump 4 (Table 6). Simultaneously, suppose its efficiency is evaluated only in terms of efficiency under the optimal operating mode $\eta_{BEP}$, under the operating mode according to the maximum value of hydraulic power $\eta_{EEI}$, and under the operating pump mode at the nominal point of the network $\eta_{NOM}$ at $Q_{NOM}$ = 100 m$^3$/h. In that case, it occupies second place according to the first two indicators in Table 6, respectively, and for the third indicator, only third place. This suggests that, in fact, choosing pumping equipment should not necessarily be limited only by the values of the equipment efficiency and its pressure-and-flowrate characteristics. The given research data indicate that it is advisable to use a relative indicator of the pump's energy efficiency for specific conditions during its operation.

The paper explored the possibility of using the energy characteristics of pumping equipment to calculate elements according to the requirements of Directive 2009/125/EU [5] and the requirements of the 2005/32/EC Regulation [6]. Accordingly, the first legislative document regulates the requirements for assessing the energy efficiency indicators of water pumps, relatively speaking, according to the optimal characteristics of the operation efficiency of such equipment. The second document, assessing the energy efficiency indicators of torque flow pumps, uses the maximum values of the corresponding hydraulic power equipment. At the same time, the results analysis of the pump energy efficiency assessment according to the energy efficiency indicators of their use indicates almost similar ranking results for the related equipment. However, there are differences related to the fact that the value of the maximum value of the hydraulic power of the pump at outlet $P_{hyd}$ is almost always more significant than the value at the point with the maximum efficiency of pump $\eta_{BEP}$. Nevertheless, there are cases when these values coincide, or the maximum efficiency of the pumping equipment is outside the regulated limits of pump operation, for example, for circulation pumps.

Overall, in most cases, the selection of a pump for the needs of the hydraulic network occurs only by choosing a pump with a flow rate with maximum efficiency ($Q_{BEP}$) as close as possible to the flow rate of the fluid in the hydraulic network. However, it should be said that the fluid flow in the hydraulic network may be changed over time. Such changes are traditionally not considered when selecting a pump.

The advantages of the proposed approach are as follows. Firstly, the research makes it possible to improve the pump selection algorithm for the needs of a real hydraulic network with a non-constant flow rate, allowing the pump to be operated with better quality indicators. As a result, this increases the energy efficiency of the pumping unit.

Secondly, this enables the pump's reliability and the inter-repair cycle's duration to be increased. This is because the highest indicators of reliability of the pump are achieved when it works in the operating range near the BEP point ($Q_{BEP}$).

## 5. Conclusions

It was established that it is essential to solve the scientific and technical problem of choosing energy-efficient pumping equipment in order to significantly improve the indicators of electrical energy consumption under liquid pumping.

An energy efficiency indicator for torque flow pump usage was proposed to improve the decision-making procedure for choosing pumping equipment for specific production conditions.

An algorithm was developed for calculating the energy efficiency indicator value for the corresponding pumping equipment usage, based on the requirements of legislative documents, i.e., Directive 2009/125/EU and requirements of the (EU) 641/2009 Regulation.

It was established that calculating the energy efficiency indicator value for the pumping equipment used, based on the basic principles of mentioned legislative acts, gives similar results. However, it is advisable, when deciding on the choice of pumping equipment, to consider the deviation of pump operation from the optimal operating mode for which it was designed for the corresponding pump. Therefore, it is recommended to use an indicator of equipment energy efficiency for the best efficiency point as a primary indicator of the energy efficiency of the pumping equipment usage. This decision should be based on comparing the pumping equipment used under the optimal operating mode to the average compensated network power values.

**Author Contributions:** Conceptualization, O.I. and V.K.; methodology, V.A. and S.P.; software, V.K. and S.W.; validation, S.P.; formal analysis, M.O., S.W., A.K. and M.M.; investigation, O.I., V.A. and V.K.; resources, M.O. and A.K.; data curation, I.P.; writing—original draft preparation, O.I.; writing—review and editing, I.P.; visualization, S.P. and V.A.; supervision, I.P.; project administration, I.P.; funding acquisition, M.O. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Polish Ministry of Education and Science, grant number 0912/SBAD/2302.

**Data Availability Statement:** Data is available on request from the corresponding author.

**Acknowledgments:** The authors acknowledge the National Research Foundation of Ukraine for the possibility of realizing the project "Development of design solutions and layout schemes of a parametric series of high-speed energy-efficient well pumps for the needs of enterprises in the field of critical infrastructure" (No. 2022.01/0096). The authors also appreciate the Public Union "Sumy Machine-Building Cluster of Energy Efficiency" (SMBCEEQ) and "International Association for Technological Development and Innovations" (IATDI) for all the support during the research.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Nomenclature

| | | |
|---|---|---|
| EEI | Energy efficiency index | |
| ISO 9906:2012 | Rotodynamic pumps. Hydraulic performance acceptance tests. Grades 1, 2 and 3 | |
| EN 16297-1 | Pumps. Rotodynamic pumps. Glandless circulators. General requirements and procedures for testing and calculation of energy efficiency index (EEI) | |
| $I_{EEP}$ | Energy efficiency indicator of equipment | |
| Symbols and Units | | |
| $\eta$ | efficiency | % |
| $H$ | Head | m |
| $Q$ | Flow rate | $m^3/h$ |
| $P_{L,avg}$ | Average compensated network power | W |
| $P_{ref}$ | Reference power at the pump inlet | W |
| $P_{L,i\%}(Q_i)$ | Network hydraulic power | W |
| $Q_i^{net}$ | Flow rate for the *i*-th network loading mode | $m^3/h$ |
| $h_{net}$ | Function that characterizes the network head rate | m |
| $P_{hyd}$ | Hydraulic output power | W |
| $\eta_{Q^*}$ | Efficiency of pumping equipment at the flow rate of pumping equipment $Q^*$ | $m^3/h$ |

## References


1. Poorly Designed Pumps Use 10% of World Energy. Available online: https://blogs.sw.siemens.com/simcenter/poorly-designed-pumps-use-10-of-world-energy/ (accessed on 4 June 2023).
2. Is Reduction of Global Electricity Consumption by 4 per Cent Possible? Available online: https://www.eco-business.com/news/is-reduction-of-global-electricity-consumption-by-4-per-cent-possible/ (accessed on 24 May 2023).
3. Andrusiak, V.O.; Lugova, S.O.; Medvid, S.A.; Tkach, P.Y.; Rudenko, A.A. Effect of front impeller seal leakages on centrifugal stage characteristics. *J. Phys. Conf. Ser.* **2021**, *1741*, 012036. [CrossRef]
4. Water and Energy Efficiency. Available online: https://sdgs.un.org/goals/ (accessed on 4 June 2023).
5. Gheorghe, C.M.; Macinic, I.-A.; Gheorghe, A.G. Oblong core cross-section impact on power transformer characteristics. *Rev. Roum. Sci. Tech. Ser. Electrotech. Energetique* **2022**, *67*, 281–286.
6. Commission Regulation (EC) No 641/2009 of 22 July 2009. Implementing Directive 2005/32/EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Glandless Standalone Circulators and Glandless Circulators Integrated in Products. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:191:0035:0041:EN:PDF#:~:text=This%20Regulation%20establishes%20ecodesign%20requirements,I%2C%20point%202(4)%3B (accessed on 25 July 2023).
7. Fontana, F. Performance Analysis of Compact Multistage Pumps Manufactured from Sheet Metal. In Proceedings of the 12th European Conference on Turbomachinery Fluid Dynamics and Thermodynamics, ETC 2017, Stockholm, Sweden, 3–7 April 2017. [CrossRef]
8. Emami, S.A.; Emami, M.H. Design and implementation of an online precise monitoring and performance analysis system for centrifugal pumps. *IEEE Trans. Ind. Electron.* **2017**, *65*, 1636–1644. [CrossRef]
9. Panchenko, V.; Ivchenko, A.; Dynnyk, O.; Drach, O. Increasing the technical level of a torque flow pump by changing the geometry of a flowing part. *Technol. Audit. Prod. Reserves* **2018**, *3*, 10–21. [CrossRef]
10. Mandryka, A.; Majid, A.P.; Ratushnyi, O.; Kulikov, O.; Sukhostavets, D. Ways for improvement of reverse axial pumps. *J. Eng. Sci.* **2022**, *9*, D14–D19. [CrossRef]
11. Kondus, V.Y.; Kotenko, A.I. Investigation of the impact of the geometric dimensions of the impeller on the torque flow pump characteristics. *East.-Eur. J. Enterp. Technol.* **2017**, *4*, 25–31. [CrossRef]
12. Gusak, A.G.; Krishtop, I.V.; German, V.F.; Baga, V.N. Increase of economy of torque flow pump with high specific speed. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *233*, 012004. [CrossRef]
13. Puzik, R.V.; Kondus, V.Y.; Pavlenko, I.V.; Antonenko, S.S. The influence of the impeller design features on the combined operating process of the torque-flow pump. *Nauk. Visnyk Natsionalnoho Hirnychoho Universytetu* **2023**, *2*, 71–76. [CrossRef]
14. Kondus, V.Y.; Puzik, R.V.; German, V.F.; Panchenko, V.O.; Yakhnenko, S.M. Improving the efficiency of the operating process of high specific speed torque-flow pumps by upgrading the flowing part design. *J. Phys. Conf. Ser.* **2021**, *1741*, 012023. [CrossRef]
15. Panchenko, V.; German, V.; Kondus, V.; Ivchenko, O.; Ryasnaya, O. Combined operating process of torque flow pump. *J. Phys. Conf. Ser.* **2021**, *1741*, 012022. [CrossRef]
16. Ejiri, E.; Kubo, M. Flow and loss analysis of a torque converter pump in the higher speed ratio range. *Trans. Jpn. Soc. Mech. Eng. Part B* **1998**, *64*, 2102–2108. [CrossRef]
17. Krishtop, I.V. Creating the flowing part of the high energy-efficiency torque flow pump. *East.-Eur. J. Enterp. Technol.* **2015**, *2*, 31–37. [CrossRef]
18. Yang, J.; Liu, B.; Zhang, T.; Hong, J.; Zhang, H. Multi-parameter controlled mechatronics-electro-hydraulic power coupling electric vehicle based on active energy regulation. *Energy* **2023**, *263*, 125877. [CrossRef]
19. Li, W.; Huang, Y.; Ji, L.; Ma, L.; Agarwal, R.K.; Awais, M. Prediction model for energy conversion characteristics during transient processes in a mixed-flow pump. *Energy* **2023**, *271*, 127082. [CrossRef]
20. KSB. Dry-Installed Pump. *Sewatec.* Available online: https://www.ksb.com/uk-ua/lc/products/pump/dry-installed-pump/sewatec/S02B/ (accessed on 24 May 2023).
21. EN 16297-1:2012. Pumps—Rotodynamic Pumps—Glandless Circulators. Part 1: General Requirements and Procedures for Testing and Calculation of Energy Efficiency Index (EEI). Available online: https://standards.iteh.ai/catalog/standards/cen/6da838fa-9c3b-4373-8328-00ed7dc7d11e/en-16297-1-2012/ (accessed on 4 June 2023).
22. EN 16297-2:2012. Pumps—Rotodynamic Pumps—Glandless Circulators. Part 2: Calculation of Energy Efficiency Index (EEI) for Standalone Circulators. Available online: https://standards.iteh.ai/catalog/standards/cen/33c0204d-1332-436b-b858-7aeeb957888e/en-16297-2-2012 (accessed on 4 June 2023).
23. EN 16297-3:2012. Pumps—Rotodynamic Pumps—Glandless Circulators. Part 3: Energy Efficiency Index (EEI) for Circulators Integrated in Products. Available online: https://standards.iteh.ai/catalog/standards/cen/0319682c-4b48-4d5a-9569-7f0aa75dee68/en-16297-3-2012/ (accessed on 4 June 2023).