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ASSESSING THE APPLICABILITY OF ENERGY STORAGE SYSTEM FOR PLUG-IN HYBRID TRACTION SYSTEM IN RAIL ROLLING STOCK

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This study examines the rolling stock that currently employs or could be equipped with plug-in hybrid traction systems.

Existing methodologies for selecting energy storage systems often limit their applicability, which creates certain constraints when choosing a solution for hybrid traction systems.

As a result of the study, a well-founded preliminary selection of an energy storage system based on expert evaluation and the Harrington desirability function was carried out.

Engaging experts in relevant fields makes it possible to obtain up-to-date information on technology development and assess whether parameters meet specific requirements. The application of methods for evaluating expert consensus provides a foundation for using the results in subsequent calculations.

Harrington desirability function makes it possible to combine parameters with varying units of measurement and other differences, yielding a single value that can simplify decision-making.

Using expert-derived evaluations, weighting coefficients for various parameters were calculated for the defined types of rolling stock.

In the current research, three types of energy storage systems were selected for locomotives and multiple-unit rolling stock, meeting the specified conditions. These include battery, supercapacitor-based and flywheel-based storage systems, with overall desirability scores (without weighting coefficients) of 0.638, 0.636, and 0.573, respectively.

Modifying the set of parameters, introducing additional constraints, and adjusting weighting coefficients in conjunction with motion optimization tasks makes it possible to adapt the methodology to the requirements for specific projects for constructing or upgrading rolling stock with plug-in hybrid traction systems

Keywords: plug-in hybrid traction systems, energy storage system, Harrington desirability function

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1. Introduction

According to some estimates, transport is the source of almost 1/5 of all CO_2 emissions [1] that occur as a result of human activities. Most of these emissions arise from the use of fuels that need to be burned to obtain energy.

Railroads account for approximately 1.9% of global fuel consumption and generate 4.2% of emissions out of the total volume of emissions from the transport sector [2].

Increasing consumption of fossil fuels leads to rapid depletion of reserves, high volatility of their cost, climate change; dependence on poorly controlled factors such as political instability and military activities increase the cost of rendering transport services.

These factors encourage designers to find ways to improve environmental, economic, and operational indicators. Principal ones are to use green energy and improve energy efficiency.

In recent decades, the use of systems for recovery, accumulation, and further use of stored energy in rail transport has become increasingly popular.

Such solutions have been implemented in the form of designing stationary (SESS) and on-board (OESS) energy storage systems. SESSs are installed near stations or along tracks, OESSs are assembled directly on rolling stock [3].

These systems may have significantly different implementation requirements depending on the functions performed, for example, compensation for short-term voltage drops in the network or storage of recuperation energy in a plug-in hybrid traction system.

Each type of energy storage system (ESS), in turn, has its distinctive set of general and specific characteristics [4], which may meet the requirements in full or in part.

Scientific research aimed at improving the processes of selection and assessment of compliance of ESS with application requirements plays an important role for their implementation in rail transport. The selection can be conditionally divided into several iterations. At the first stage, it is advisable to consider ESSs that meet the basic requirements characteristic of rolling stock, in particular operating temperature range, calendar life, cost, etc. Subsequently, the initial choice can be optimized taking into account specific operating conditions and the current level of development of energy conversion and storage technologies.

The correct choice of ESS affects the autonomy of rolling stock and allows it to be used during power outages or in areas where electrification is too expensive or complicated.

The results of such studies are needed in practice because the compliance of ESSs with the established tasks is one of the key components for making a decision on the application and further operation of the system.

Therefore, studies on assessing the basic characteristics of ESSs and the possibility of their use in plug-in hybrid traction systems are relevant.

2. Literature review and problem statement

In reviews that examine hybrid rolling stock, one or more ESS variants are mainly considered. These are battery electrochemical energy storage (BESS), supercapacitor-based storage (EDLC), flywheel inertial storage (FESS), and superconducting magnetic energy storage (SMES).

According to study [5], the functions of ESS depend on the type of rolling stock, which can be divided into two large groups: passenger and freight. The work focuses on reviewing examples of real-world applications of ESSs in urban and regional passenger rolling stock, in particular BESS, EDLC, and fuel cells. The study does not provide a structured methodology or algorithm for selecting the type of ESS depending on the type of rolling stock or operating conditions. This is probably due to the different approaches of rolling stock manufacturers to the implementation of projects using ESSs and the lack of uniform standards for such systems. The issues of ESS service life are mentioned but remain beyond detailed consideration. This may be due to the lack of access to operational data because of NDA or similar restrictions.

In contrast to [5], paper [6] provides an overview of the current state of OESS application for a wider range of rolling stock types, and the issues of ESS durability are discussed in more detail. It also provides forecasts for the further development of more environmentally friendly hybrid systems based on the use of a combination of ESSs and hydrogen fuel cells. To assess the effectiveness of the possible application of ESSs, the prospect of modeling using digital twins and artificial intelligence technologies is emphasized. However, specific modeling tools are not described in the study. A likely reason for the lack of analysis of ESS selection methods may be the difficulty of collecting reliable data on the procedures used by manufacturers.

An approach using real data for modeling is used in [7]. It considers a hybrid traction unit for a freight locomotive using hydrogen fuel cells and lithium-ion batteries (LIB). The methodology is based on data collected for a diesel locomotive with electric transmission on specific routes. The required battery capacity is simulated based on real data and compared with previous analytical calculations. According to the authors, the actual required battery capacity is larger than the values obtained in previous studies. In [7], BESSs or hydrogen fuel cells are considered and other types of ESSs are not included in the calculations. This may be due to the authors focusing on a specific application to be able to verify and compare the simulation results with real data for specific locomotives and routes.

An approach considering real-world applications and a larger number of ESS types than in [7] is used in [8]. In it, to ensure the operation of electric LRV in cities on areas without electrification, the authors propose a modernization using ESS. These are LIBs with different chemistries, EDLCs, and lithium-ion capacitors (LiC). The choice of the feasibility of using a particular type of ESS is made on the basis of their quantitative indicators and requirements for operation routes. Although the authors present an analysis of the possibilities of using BESS, EDLC, or LiC, only LRVs are considered. Such an approach narrows the scope of the results obtained and does not provide reasonable conclusions regarding their use with other types of rolling stock. This approach may be due to the fact that only rolling stock with a small mass is suitable for operation in an urban environment with dense construction. Therefore, other types of ESSs may not meet technical or operational requirements.

A more comprehensive study, which is aimed at a wider range of ESS types and rolling stock, is reported in [9]. The paper highlights the advantages and disadvantages of various ESSs, such as BESS, EDLC, FESS, SMES. The authors note that EDLC is more often used for the accumulation of regenerative braking energy (RB). To provide power on certain non-electrified sections of the track, BESSs and their combinations with EDLC are more typical. A general approach to the selection of ESS is outlined without taking into account the features of the route and specific operating modes; basic gravimetric and volumetric indicators are taken into account. In [9], the authors focused on general technical and economic aspects, so the issues of operation, maintenance, and disposal remained outside the scope of in-depth analysis. Despite the mention of hybrid systems, the paper does not provide their technical analysis and methods for selecting ESSs for different types of rolling stock. The reasons for the unresolved issues may lie in the large variability of operating conditions and limited access to data from railroad operators.

In [10], the modernization of suburban diesel trains is considered. The proposed option includes the implementation of a plug-in hybrid traction unit using BESS. The calculations and modeling for the given conditions indicate that such plug-in hybrid systems allow for a significant reduction in fuel consumption due to the accumulation and use of RB energy. The authors focus on the characteristics that ESS should provide. Despite the consideration of various technical parameters, the paper does not describe the methodology for selecting a specific type of ESS. This is probably due to the narrow subject matter of the project or predetermined initial data.

The selection of an energy storage device using a multi-criteria decision-making model (MCDM) taking into account various specific requirements for network applications is proposed in [11]. The analysis used data obtained from experts and from literary sources. When selecting the necessary energy storage technology, the authors propose using the ordering by similarity to the ideal solution (TOPSIS). This method makes it possible to rank alternatives by their proximity to the ideal solution and distance from the worst.

In [12], the results of studies on the selection of energy storage technology are reported. The MCDM model is applied using the decision-making method based on probabilistic dual uncertain fuzzy sets (PDHFS) and expert assessments. In order to analyze the applicability of a certain type of ESS, the authors propose to take into account specific storage needs that have not been taken into consideration in many previous studies. The authors propose to divide the selection criteria into 4 groups: technological, economic, environmental, and social.

The methodologies presented in [11, 12] are more generalized or tied to specific applications, while the issue of choosing technologies for transport remains outside the scope of consideration. One of the possible reasons for such limitations may be the difficulty of involving specialists from all areas of ESS application.

Study [13] reports the results of ESS selection for rail rolling stock using the Harrington desirability function. Several types of ESSs were analyzed, in particular BESS, EDLC, FESS. The main quantitative parameters that influence decision-making on the final choice of a specific type were determined. For the considered ESS, in accordance with the established parameters, the general desirability coefficients were calculated.

At the same time, when choosing the ESS type, the issue of determining the reliability of estimates and the influence of weighting coefficients depending on the type of rolling stock was not taken into account. Such limitations may be due to the fact that the study focuses specifically on the selection of ESSs, and not on the evaluation methodology.

Our review of the literature [5–13] demonstrates that despite numerous studies in the field of ESS selection for hybrid traction units and similar applications, there are a number of local problems that require further study. When choosing the ESS type, a large amount of input data and restrictions imposed on projects during their implementation should be taken into account. The wide range of ESSs further complicates the task of selection.

The systematization of the identified aspects allows us to state that most sources limit the scope of application, the scope of parameters and characteristics or the type of ESS that are taken into account when conducting research. Also, most often, when involving experts, the results of assessing the consistency of their opinions are not provided. Therefore, it is advisable to conduct a study aimed at performing a substantiated initial selection of ESSs for plug-in hybrid traction systems of rail rolling stock.

3. The aim and objectives of the study

The purpose of our study is to evaluate and initially select the type of ESS that meets the basic requirements for use in plug-in hybrid traction systems on railroad rolling stock. This could make it possible to reduce the number of combinations between ESSs and types of rolling stock and reduce the volume of further calculations.

To achieve this aim, the following objectives were accomplished:

– to analyze existing types of ESSs that can be used in hybrid plug-in traction systems of rail rolling stock;

– to determine the basic and common parameters of different types of ESSs that would be most important for rail rolling stock;

– to select a list of types of railroad rolling stock on which plug-in hybrid traction systems can be implemented;

– to compile a table for expert assessment of parameters and check the consistency of expert opinions using statistical analysis tools;

– to determine the weighting factors according to application and calculate the overall desirability of different ESSs for a certain type of rolling stock (with the possible presence of parameter weighting factors).

4. The study materials and methods

The object of our study is rail rolling stock, which in the future could be retrofitted or built using hybrid plug-in traction systems.

Within the framework of the work, the following hypothesis was proposed: at the first stage, the selection of ESS for different types of rolling stock can be performed using a combination of expert assessment methods and Harrington desirability function.

The work assumed that as a result of the calculations, the desirability value is characterized by a linear dependence on the parameters being evaluated and does not depend on whether they are quantitative or qualitative. It was also assumed that the parameters proposed for expert assessment are common to all types of ESSs considered in their analysis.

We have adopted the following simplification: ESSs are categorized into generalized types according to their nature. Detailed intragroup differences (for example, specific BESS chemistry) were not considered at this stage.

For the evaluation, the experts were provided with two questionnaires:

– in questionnaire No. 1, the experts assessed the importance of ESS parameters for a certain type of rolling stock on a scale from 1 (minimal impact) to 5 (strong impact) on the traction system;

– in questionnaire No. 2, a list of ESS quality indicators is provided, section 5.2. For the evaluation, a graduation from 1 to 10 was determined, the higher the expert assessed the parameter, the better, in his/her opinion, this indicator for the ESS.

Given that the evaluation was not carried out by the parameter ranking method and the number of repeated assessments could be very high, the intraclass correlation (ICC) method was used to determine the consistency of expert opinions. ICC is defined as the correlation between two measurements obtained for one object: one measurement (a separate assessment or the average of several assessments) and another measurement obtained for the same object [14]. It makes it possible to determine what proportion of the total variance of the results is due to real differences between objects, and not to random or systematic differences in the judgments of the assessors.

According to [15], a two-factor model with mixed effects $ICC\,(3, k)$ was chosen, which makes it possible to determine the reliability of the average value of the assessments obtained from a specific group of assessors.

With an ICC value below 0.5, the consistency is considered low, in the range of 0.5–0.75 – moderate, 0.75–0.9 – good, above 0.9 the consistency is excellent.

For calculations, the Pingouin software library [16] was used, which makes it possible to statistically analyze data using various methods. The code execution environment was determined to be Google Colaboratory.

To summarize the results of the expert survey and determine the suitability of a particular type of ESS for hybrid plug-in traction systems, the Harrington multi-criteria optimization method was used.

According to this method, each measurement or criterion is converted into a dimensionless desirability scale, which takes values in the interval from 0 to 1 [17]. This allows for comprehensive work with criteria of different nature (quantitative, qualitative, with different units of measurement).

It is generally accepted to divide the Harrington function scale into 5 intervals: 0.8–1, 0.63–0.8, 0.37–0.63, 0.2–0.37, 0–0.2. For convenience, corresponding linguistic assessments are assigned to each interval: very good, good, satisfactory, poor, very poor.

The individual desirability of parameter d for a function with a one-sided restriction is calculated from the following formulas:

$$d_i = \exp\left[-\exp\left(-kY_i\right)\right], \quad (1)$$

$$d_i = \exp\left[-\exp\left(kY_i\right)\right], \quad (2)$$

where d_i is the individual desirability of the parameter, Y_i is the value of parameter Xi after linear transformation, k is the coefficient that determines the steepness of the desirability curve; it is additional and may not be used.

In the case when the individual desirability increases with the increase in the parameter value, formula (1) is used; when the desirability decreases, formula (2) is applied.

The one-sided S-shaped curve of the Harrington desirability function with intervals and linguistic counterparts, constructed according to formula (1), is shown in Fig. 1.

Fig. 1. S-shaped desirability curve

Since desirability can be calculated for parameters that are different in nature, it is first necessary to convert the values to a dimensionless scale. This can be done using a linear transformation according to the following formula

$$Y_i = b_{0i} + b_{1i}X_i, \quad (3)$$

where b_0 and b_1 are free coefficients.

If it is necessary to set the limits for parameter values, after which desirability takes value 1 or becomes equal to zero, one can additionally adjust b_0 and b_1.

The overall desirability is calculated as the geometric mean from the following formula

$$D = \sqrt{d_{i1} \cdot d_{i2} \cdots d_{in}}, \quad (4)$$

where D is the overall desirability, d_i is the individual desirability of the i-th criterion, n is the number of criteria.

The calculation according to formula (4) assumes that all indicators of individual desirability have the same weight. In cases where parameters may have different effects, it is appropriate to use weighting factors that are set in advance or determined during development. The calculation of overall desirability with weighting factors is performed according to the following formula

$$D = \left(d_{i1}^{\omega i} \cdot d_{i1}^{\omega i} \cdot \dots \cdot d_{n1}^{\omega n}\right)^{\frac{1}{\Sigma \omega i}}, \quad (5)$$

where ωi is the weight coefficient of the parameter; usually; the sum of the weights ωi is taken equal to 1, d_i is the individual desirability of the i-th criterion; n is the number of criteria.

When calculating overall desirability D according to formulas (4), (5), we find it necessary to pay special attention to the fact that it is zeroed in the presence of at least one individual desirability di, which is equal to zero.

5. Results of research on the possible application of ESSs for plug-in hybrid traction system

5. 1. Analysis of ESS types that can be used in plug-in hybrid traction systems

BESSs are characterized by acceptable gravimetric and volumetric indicators, moderate requirements for maintenance and operation, as well as high reliability [3, 6]. At the same time, their disadvantages include limited charge-discharge speed characteristics, problems with thermal acceleration [18], which complicates their use under conditions of large and short-term peak loads.

EDLCs have high indicators of the number of charge-discharge cycles (cycle life), specific power, and can effectively work under high cyclic loads; the depth of discharge can reach 0%. At the same time, they have low specific energy density and high self-discharge compared to conventional capacitors and BESSs. This makes them promising for use in light rail transport [8, 19] as the main or additional component in combined types of ESSs as part of plug-in hybrid traction systems. The amount of energy stored in FESS depends on the mass of the rotor, its speed of rotation, and friction losses [20].

The main means of improving their characteristics are increasing the mass and/or increasing the speed of rotation of the rotor, the use of composite materials and magnetic bearings, as well as housings with pumped air. FESSs are very close in their energy performance to EDLCs and can be considered for use in systems where it is necessary to compensate for sudden peak jumps in load or voltage [21].

Due to the low specific energy density, the presence of large flywheel masses, high self-discharge, gyroscopic effect, and the danger posed by the flywheel in case of its destruction, the use of FESSs in rolling stock is limited.

Compressed air storage systems (CAESs) can be conditionally divided by pressure level: low-pressure systems (usually their operating pressure is up to 1 MPa) and high-pressure systems (operating range from 10 to 50 MPa) [22]. Such systems are characterized by low specific power, specific energy density and efficiency, as well as the need to use large tanks. However, it can be noted that CAESs are environmentally friendly and could be used as additional components.

Hydraulic energy storage systems (HESs) operate on principles similar to CAESs, but they use liquid instead of air. They have high efficiency when working under frequent charge-discharge cycles; their structure is quite simple. At the same time, precession systems are required for control, and the energy storage time ranges from a few seconds to minutes. Such characteristics indicate their similarity to EDLCs [23] and the possible scope of their application for short-term repetitive loads.

SMESs have high values of specific power and cycle life without deterioration of characteristics. However, the need to use a complex cooling system and temperature maintenance and low specific energy consumption significantly increase the mass and cost of the system. As a result, their application on transport is mainly experimental. However, work is underway to improve their characteristics, which makes SMESs promising for future use.

5. 2. Determining common ESS parameters that are most suitable for use on rolling stock

To evaluate and compare different types of ESSs, it is advisable to divide their characteristics into two groups:

– quantitative indicators that are subject to mathematical and statistical analysis and can be expressed in numerical form;

– qualitative indicators that describe the properties of the object and are difficult to express directly in numbers.

The choice of common indicators characteristic of different types of ESSs also depends on their operating modes. For rail rolling stock, the main operating modes are acceleration, constant speed movement, and braking.

As a result of analysis, the correspondence of the frequency of use of various parameters for the listed modes was obtained without reference to the type of rolling stock. This dependence is shown in Fig. 2.

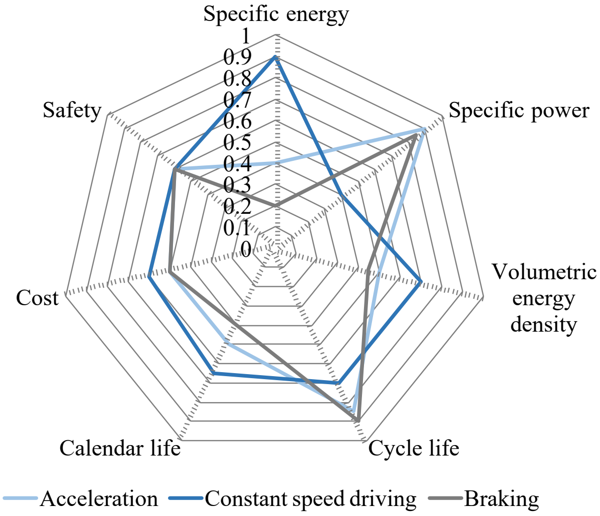

Fig. 2. Correspondence of parameters to different driving modes

Value 1 in the diagram corresponds to a high frequency of use; zero: the parameter for the specified mode is almost not used.

According to [3, 5, 7–9, 12] and dependences in Fig. 2, the basic energy indicators by which ESSs are assessed are specific energy Wh/kg, specific power W/kg; volumetric energy density Wh/l (or Wh/m^3).

Important assessment criteria that can be attributed to quantitative ones are the cost indicators of ESS, installation, auxiliary equipment, and operation. In addition, indicators that exert a significant impact on decision-making are calendar life and cycle life until the minimum permissible capacity is reached.

For rail vehicles, a large part of the system life cycle is made up of operating costs. They are closely related to the following group of characteristics: mean time between failures (MTFB), operational safety, operating temperature range, maintenance frequency (regularity), and environmental issues.

These indicators are accepted as common for the specified types of ESSs.

5. 3. Determining the types of rolling stock where plug-in hybrid traction systems can be implemented

According to the resolution from the Cabinet of Ministers in Ukraine [24], the following list of rolling stock has been established: locomotives; multiple-unit rolling stock; locomotive-hauled passenger cars; freight cars; special rolling stock of railroad transport; components of rolling stock for railroad transport.

For different types of rolling stock, the existence or duration of driving modes may differ, which directly affects the requirements for ESSs, for example [25, 26]. The directions of energy flow for the main driving modes are shown in Fig. 3.

Considering that our research is focused on plug-in hybrid traction systems and possible operating modes, Fig. 3, the following types of rolling stock were selected:

– passenger and freight locomotives;

– shunting locomotives performing work at stations and hills (yard switcher);

– shunting locomotives performing removal work (transfer locomotive);

– distributed traction multiple unit (MVRS);

– trains with engines in the main cars.

Special rolling stock also has prospects for implementing ESSs, for example [26], but it requires separate additional research because of specific operational requirements.

5. 4. Construction of tables for expert assessment of parameters and determining the consistency among experts' opinions

For convenience of assessment, the questionnaires were divided into two parts. The first included 17 parameters defined in section 5. 2 and 6 types of rolling stock, section 5. 3. The second questionnaire contained a list of qualitative parameters that the experts assessed in accordance with the ESS type.

Their assessment was carried out by a group of 8 experts. In Table 1, part of the second questionnaire is given, with parameter assessments from expert 5.

When checking the consistency, the ratings from each expert were summarized in a common table. Further analysis was performed according to formula (6) using the library from [16]

$$ICC(3,k)=\frac{MSR-MSE}{MSR+(k-1)MSE}, \qquad (6)$$

where MSR is the mean square for rows (intersubject variance), MSE is the mean square error (residual variance), k is the number of experts.

The calculation of consistency using the $ICC\ (3,\ k)$ method was performed for each specified type of rolling stock. The results are given in Table 2.

The calculated $ICC\ (3,\ k)$ value is in the range of 0.5–0.75 for all questionnaires and can be interpreted as moderate agreement among the experts.

The F-statistic is necessary to test the null hypothesis that the true ICC value is zero and indicates the statistical significance of the result.

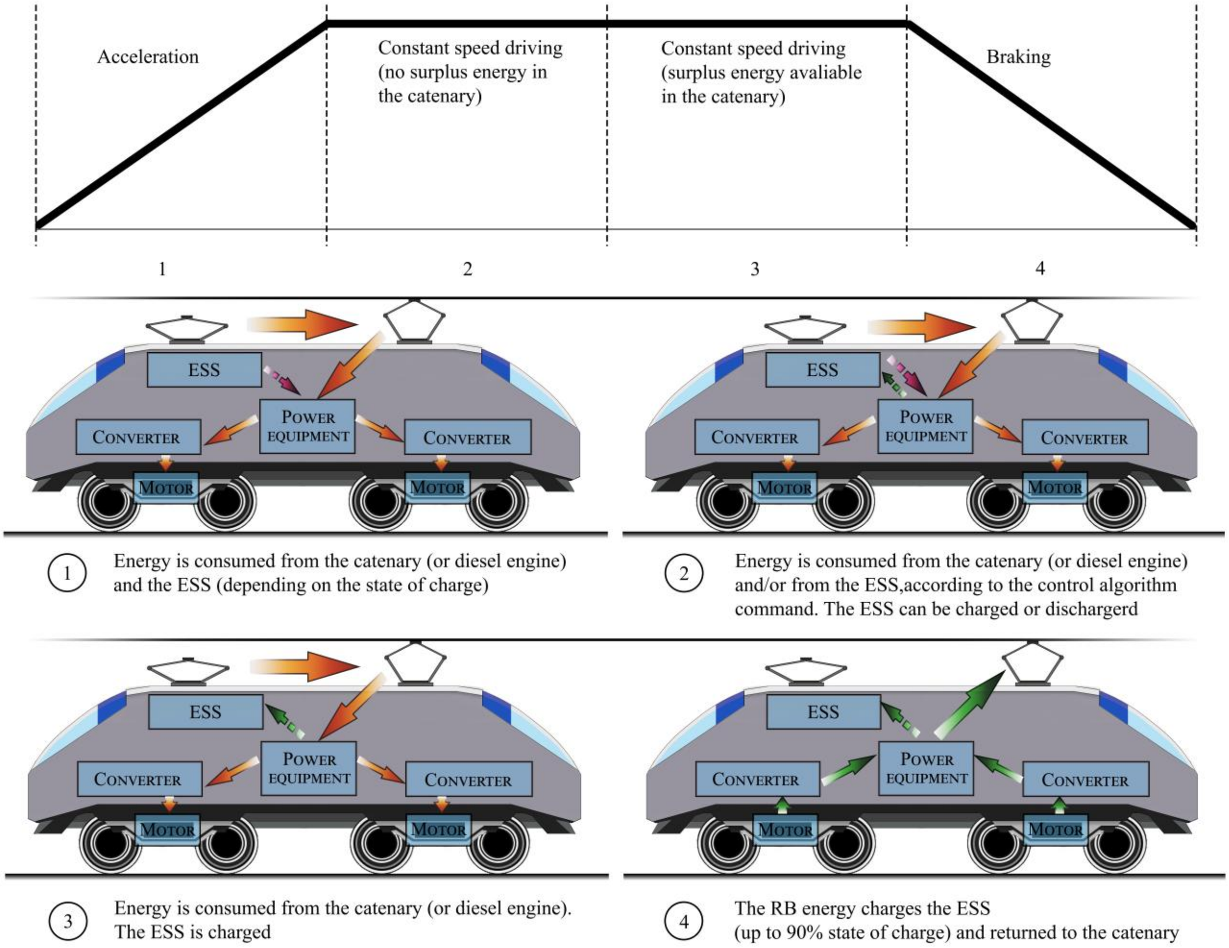

Fig. 3. Rail rolling stock operating modes

Table 1

Expert 5 ratings

Parameter being evaluated	ESS type					
	BESS	EDLC	FESS	CAES	HES	SMES
Operating temperature range	8	9	9	8	8	3
Calendar life	9	10	10	9	9	9
Operational safety	10	9	7	7	7	8
Overheating rate	7	6	6	6	6	4
Maintenance regularity	7	8	7	7	7	7
Quick replacement capability	8	8	6	6	6	5
Technology development potential	10	9	9	8	8	10
Environmental friendliness of operation	9	10	10	10	8	9
Environmental friendliness	8	9	8	9	7	6
Additional equipment	6	7	7	7	7	10

Table 2

Consistency among expert opinions

Rolling stock type		*ICC* (3, *k*)	F-stat	p-Value	CI95%
Locomotives	Passenger	0.698	3.3	0.0001	0.42–0.87
	Freight	0.693	3.26	0.00012	0.41–0.87
	Yard switcher	0.647	2.836	0.00069	0.32–0.85
	Transfer locomotive	0.681	3.13	0.0002	0.39–0.87
Distributed traction	MVRS	0.547	2.2	0.0085	0.13–0.81
	With engines in the main cars	0.696	3.29	0.0001	0.42–0.87

The p-Value values less than 0.05 allow us to draw the following conclusion: the agreement is not random but statistically confirmed. CI95% shows that the true ICC value is in the specified range with a 95% probability. The obtained CI95% indicators are in the interval between "acceptable" and "unstable".

Based on the calculated values, a decision was made on the validity of our results and their further use in the study.

5. 5. Determining the weight coefficients and general desirability of different types of ESSs for rolling stock

The calculation of weight coefficients was performed for each parameter as an arithmetic mean estimate from all experts relative to the maximum value on the established scale in questionnaire 1 for each type of rolling stock.

To calculate the desirability coefficient, the values of quantitative indicators were taken from the literature [3, 5–7, 9, 20, 22, 23].

When calculating each individual desirability coefficient, the upper limit, y_1, was set at 0.8 and equal to the maximum indicator of this parameter among all types of ESSs; the lower limit, y_2, at 0.2, respectively.

For points y_1 and y_2, the values on the dimensionless scale y' were found from formula (7) for the case "the more, the better" and formula (8) for the parameters "the less, the better", respectively. They are common for calculating all individual parameter desirability:

$$y_1' = -\ln\left(-\ln\left(y_1\right)\right), \tag{7}$$

$$y_2' = \ln\left(-\ln\left(y_2\right)\right). \tag{8}$$

The coefficients b_0 and b_1 are calculated based on formula (3) and depend on the minimum and maximum values of the parameter. The results from our calculations of the required coefficients are given in Table 3.

The values of qualitative parameters were obtained by averaging the estimates given by experts in questionnaire 2 and taking into account the characteristics from [3, 5–7, 9, 20, 22, 23].

The transition from linguistic estimates to numerical values was performed according to the following correspondences: very good – 0.95; good – 0.80; satisfactory – 0.63; poor – 0.20; very poor – 0.05.

Part of the calculated weight coefficients for passenger and freight locomotives is given in Table 4.

The calculated overall desirability coefficients according to formulas (4), (5) are given in Table 5.

A graphical distribution of overall desirability between different types of rolling stock and ESS types is shown in Fig. 4.

Based on our results, it can be determined that the most suitable ESSs for the established conditions are BESSs, EDLCs, and FESSs.

Table 3

Coefficients for calculating individual desirability

Parameter	y'_1	y'_2	b_0	b_1
Specific power, W/kg	–0.4759	1.4999	–0.6170	0.0014
Specific energy, Wh/kg	–0.4759	1.4999	–0.5265	0.0101
Volumetric energy density Wh/m^3,	–0.4759	1.4999	–0.4883	0.0000
Cost per 1000 Wh	0.4759	–1.4999	–1.7195	0.0022
Permissible depth of discharge (DOD), %	–0.4759	1.4999	–3.2985	0.0565
Cycle life	–0.4759	1.4999	–0.6477	0.0000
Calendar life	–0.4759	1.4999	–2.4517	0.1976

Table 4

Weighting factors

Parameter	Passenger locomotive		Freight locomotive	
	Estimate	Weighting factor	Estimate	Weighting factor
Specific power, W/kg	4.625	0.07	4.375	0.065
Specific energy, Wh/kg	4.375	0.066	4.625	0.069
Volume energy density, Wh/m^3	4.250	0.06	4.375	0.065

Table 5

General desirability coefficients for different types of rolling stock and ESSs

ESS type	Overall desirability taking into account weighting factors according to the type of rolling stock						Overall desirability without weighting factors
	Passenger locomotive	Freight locomotive	Yard switcher	Transfer locomotive	MVRS	Trains with engines in the main cars	
BESS	0.622	0.628	0.627	0.627	0.631	0.630	0.638
EDLC	0.627	0.618	0.623	0.622	0.631	0.628	0.636
FESS	0.567	0.559	0.565	0.561	0.570	0.566	0.573
CAES	0.284	0.283	0.287	0.283	0.289	0.285	0.290
HES	0.347	0.318	0.349	0.346	0.353	0.347	0.358
SMES	0.324	0.333	0.321	0.318	0.325	0.322	0.316

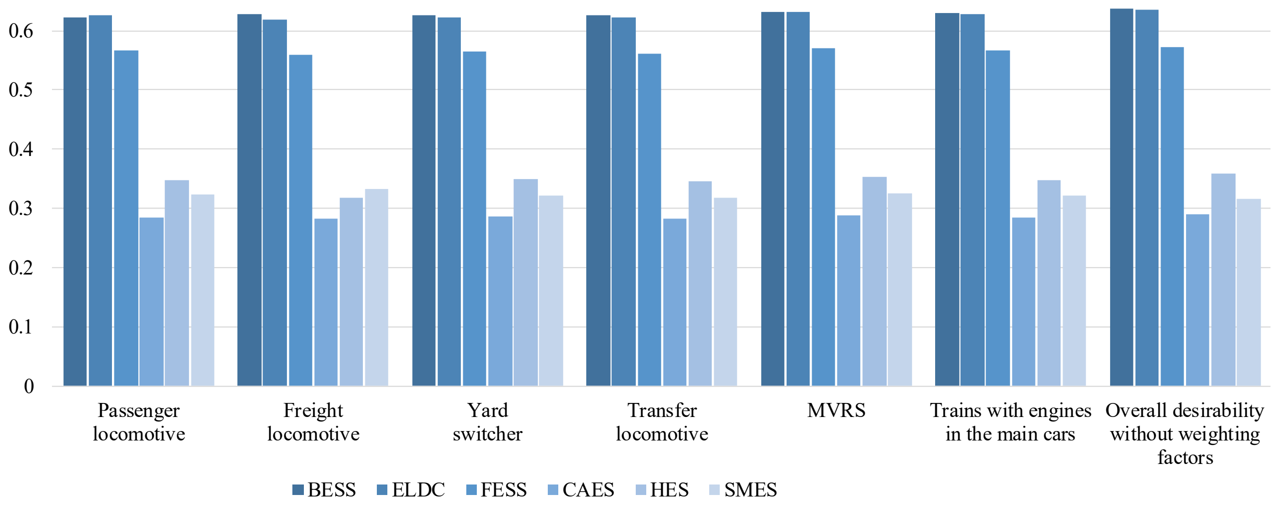

Fig. 4. Distribution of desirability of different types of energy storage for rolling stock

6. Discussion of results based on the possible application of ESSs for plug-in hybrid traction systems of rolling stock

Our study used ESS characteristics, which include both quantitative and qualitative indicators. A significant part of them, for example, shown in Fig. 2, can be evaluated according to the criteria "the more, the better" or "the less, the better". However, although some of the indicators are expressed in numerical values, their assessment may significantly depend on the type of ESS and the tasks set. For example, the operating temperature range of a certain type of ESS may fully meet the criteria of one project and not fit into the requirements for another at all. For such characteristics, a linguistic scale was used, Fig. 1, the correspondence of numerical values for which was determined using expert assessments. This allows them to be used for general assessment without reference to specific applications, which differs from the approaches proposed in [7, 10], which focus on individual applied tasks.

The division of questionnaires makes it possible to determine the most appropriate parameters for the system and to involve experts from different fields, which increases the quality of the assessment.

During the survey, experts were not limited to the number of identical assessments or the mandatory use of all levels of the scale. With this approach, methods focused on the analysis of rank values, such as concordance or Spearman coefficients, do not provide correct interpretation of the results because of the loss of sensitivity to repeated values. The *ICC* (3, *k*) method used in the study makes it possible to work with such assessments. This becomes important during the initial selection of ESS type for plug-in hybrid systems since the specific conditions at this stage may not be determined and objective ranking of parameters by their importance is complicated.

Unlike work [12], in which expert assessments are used without consistency analysis, the approach proposed in our study makes it possible to immediately determine the reliability and validity of the acquired data, Table 2. This also allows for an informed decision to further use the data obtained or to conduct a re-survey or replace the sample of experts.

Determining the importance of parameters and calculating their weight coefficients, Table 4, allows for an improvement in the quality of the choice taking into account the type of rolling stock.

Using the Harrington desirability coefficient provides an informed initial choice of the most suitable type of ESS for the established conditions. Bringing the value of many parameters, different in nature, to a single number optimizes the decision-making process.

The methods used in our work do not require complex mathematical implementation, unlike [11, 12], and make it possible to simplify the task of initial selection at the stage of preliminary analysis. Further evaluation with the involvement of additional and specific requirements and the use of more complex MCDMs can be carried out for a smaller number of predefined ESS options for specific types of rolling stock, Fig. 4.

As a result of the initial selection for further research, according to Table 5, the ESSs with the highest desirability coefficients were selected: BESS (0.638), EDLC (0.636), and FESS (0.573). In addition to these ESSs, it is also worth considering the feasibility of their combination. Such solutions could improve the overall characteristics of the system by using the strengths of each type of ESS. However, analysis must also take into account possible disadvantages, such as system complexity, increased cost of its installation, and maintenance.

Based on the results of our work, the following limitations should be noted:

– not all available ESS characteristics were used in the evaluation;

– most of the parameters used have almost the same weight when calculating desirability, which is not always correct for all applications;

– numerical values of parameters obtained from literary sources may not fully reflect the current state of technology development;

– intragroup differences of different types of ESSs are left outside the scope of this work and require further consideration;

– the type of the main power source of the rolling stock was not taken into account at this stage of the study;

– 8 experts were involved in the evaluation, which affects the reliability of the results, as can be seen from the CI95% indicators in Table 3.

The following are among the shortcomings of the study:

– most of the parameters used have almost the same weight when calculating desirability, which is not always correct for all applications;

– combinations of different types of ESSs are not taken into account in the current study and require separate consideration.

For future studies, to increase reliability, it is desirable to increase the number of experts and explore the possibility of using rank-order methods.

In subsequent iterations of the selection, it is advisable to perform additional calculations for specific types of rolling stock and supplement the list of parameters for evaluation. For example, the type of main power source, maximum coupling weight, overall dimensions, required power, capacity, etc.

In addition, it is necessary to take into account the parameters of the track profile, the existence of a contact network, speed modes of movement, and other similar requirements. This creates the prerequisites for combining the tasks of selecting the ESS type and optimizing train movement.

7. Conclusions

1. The following types of ESSs have been identified: BESS, EDLCs, FESSs. Since no restrictions were set on the maximum mass, volume, or cost of the system at the first stage of selection, the list also includes promising types of ESSs, such as CAESs, HESs, and SMESs. Their application is currently theoretical or experimental in nature but is possible in the future with the advancement of technologies. This approach makes it possible to expand the scope of consideration of ESS types compared to previous studies.

2. A list of quantitative and qualitative parameters has been formed that are common to different types of ESSs and relate to rolling stock. The quantitative indicators include specific power, energy and volumetric energy density, cost per Wh, permissible depth of discharge, cycle life, calendar life. The group of qualitative indicators includes parameters related to temperature conditions of operation, maintenance, environmental friendliness of manufacturing, operation, disposal, and development potential of ESS technology. Assessment taking into account the prospects of technology development provides the opportunity to make a choice oriented towards future requirements and trends.

3. A list of types of rail rolling stock was determined that meets the general requirements for modernization using hybrid traction units. The selected rolling stock was differentiated by the main type of work performed: passenger, freight, shunting locomotives, and MVRS. The selection of traction units with different purposes makes it possible to compare the importance of certain ESS parameters for a specific application. At this stage, specific operating conditions were not taken into account, which makes it possible to check the correctness of the initial selection at subsequent stages using additional requirements.

4. For the evaluation, a list of rolling stock types and ESS parameters were determined, which were divided into two tables. When conducting the evaluation, the following requirements were set: for the first questionnaire, a scale from 1 to 5; for the second – from one to 10; without limiting the number of repetitions or the need to use each assessment. The questionnaires were given to 8 experts in the field of electric drive and energy storage. The following consistency values were calculated for locomotives using the *ICC* (3, *k*) method: passenger – 0.698; freight – 0.693; yard switcher – 0.647; transfer locomotive– 0.681. For rolling stock with distributed traction: MVRS – 0.547; with engines in the main cars – 0.696. The calculated results are in the range of 0.5–0.75, which, according to the accepted classification, means moderate agreement among experts and justifies the further use of the obtained estimates.

5. According to the calculated weighting factors, it can be noted that the obtained values are almost the same for all types of rolling stock and do not have a significant impact on overall desirability. This is explained by the fact that the main ESS parameters were evaluated without reference to specific operating conditions or additional requirements by which the importance of the indicators could be ranked. The calculated overall desirability, without taking into account the weighting factors, is for BESSs – 0.638; EDLCs – 0.636; FESSs – 0.573; CAESs – 0.29; HESs – 0.358; SMESs – 0.316. Our results are consistent with current trends in the use of ESSs on rail rolling stock, which confirms the feasibility of conducting a preliminary selection.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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