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APPLICATION OF MULTI-CRITERIA ANALYSIS FOR THE SELECTION OF POWER SUPPLY SYSTEM FOR ELECTRIFICATION NEW LINES IN THE EXISTING RAILWAY NETWORK ENERGIZED BY 3 KV DC SYSTEM

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***Abstract**:*

Electrified railways are practically the only mass transport system meeting sustain-able transport requirements of the European Green Deal policy, driving the inter-est, worldwide and in Europe, in constructing new railway lines or modernizing the existing ones. Due to differences between power supply systems in Europe, TSI standards have been issued to make railways interoperable. When a new high-speed rail line is to be built, it uses AC power supply system as it has larger power capac-ity than DC systems. However, in some countries, like Poland, a vast railway net-work is electrified with 3 kV DC. There are plans for intensive construction of new railway lines, building interconnections between the existing ones, or high-speed lines Warsaw-Łódź-Poznań/Wrocław (electrified with 25 kV AC). This raises a problem: which power supply system should be chosen for these new lines: the existing 3 kV DC or the new 25 kV AC? This paper proposes a new approach help-ful in undertaking such decisions for a specific line with the application of multi-criteria analysis (MCA), considering economic and non-economic criteria. Specific circumstances of Polish railway lines (12150 km electrified under 3 kV DC) and other aspects, such as grid network availability, construction time, and usage of the existing infrastructure, are also considered. The novelty of the presented in the paper research is seen in identification and scaling criteria for application in MCA to support decision making (MCDM) which type of a power supply system 3 kV DC or 25 kV 50 Hz is optimal to be chosen for a specific railway line in an area of densely spread existing railway lines supplied by 3 kV DC system. A review and discussion of the available in the literature research on MCA applied for MCDM in area of energy systems is enclosed, when conflicting qualitative and quantitative criteria are to be taken into account. Examples of application of the MCA method to support under-taking decision on type of a power supply for railway lines planned to be electrified are as well presented.

Keywords: *railway electrification, AC and DC power supply system, multi-criteria analysis, eco-nomic criteria, TSI criteria*

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1. Introduction

According to (Burak-Romanowski,2025) data for the year 2023, the railway network in Poland covers 18916 km of railway lines in operation. The total length of electrified lines is 12150 km. This means, that 64.2% of the network is operated with electric traction. Polish railways are electrified under a 3 kV DC system and fulfil a strategic role in transport due to a lack of own crude oil resources. Over 90% of railway transport service is performed by electric traction, mainly thanks to concentration of operational work on electrified sections.

The electrification of the Polish railway network started in 1936. The process of electrification was particularly intensive in 1980s, when approximately 500 km of lines per year were fitted for operation with electric traction. In early 1990s the electrification was stopped almost completely for more than 25 years. Quite recently several electrification projects have been undertaken, and some of them have been completed, for example Wegliniec – Zgorzelec (26 km) in 2019, Lublin – Stalowa Wola Rozwadów (95 km) in 2020, Ocice – Rzeszów (67 km) in 2021, Zawiercie – Tarnowskie Góry (46 km) and Pomeranian Metropolitan Railway in Tri-City (20 km) in 2023.

Investments concerning improvement of stations and infrastructure areas to make them more energy efficient are as well considered (Nowotarski at al.,2024; Technical Standards..,2022).

The overhead catenary is still the most effective way of supplying high-power vehicles with electrical energy, and it allows trains to reach speeds up to 350 km/h. Electrified railways are practically the only mass transport system meeting sustainable transport requirements of the European Green Deal policy, driving the interest, worldwide and in Europe, in constructing new railway lines or modernizing the existing ones (https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240313-1). The results of studies derived for Baden-Württemberg stated (RailJournal, 2025), that hydrogen as a fuel for railway vehicles is still not matured enough and catenary supplied, or hybrid (battery-catenary) vehicles are more cost-effective solutions and environmentally friendly for till now non-electrified railway lines.

The most pressing tasks in Poland concerning catenary traction are as follows:

- to increase the usage of the existing 3 kV DC railway network, and increase the speed up to 200-230 km/h at the CMK line,
- to conduct studies and design work to prepare railway operators and industry in Poland for a new 2x25 kV 50 Hz power supply system on new lines (CPK projects (https://www.cpk.pl/en/, 2024) and Rail Baltica section (new high-speed lines).

It requires:

- appropriate development of power plants, power utility system and transmission lines,
- construction of a test section of 2x25 kV 50Hz supplied line,
- support of Polish railway industry,
- development of new methods and devices for the diagnostics, monitoring and operation of traction substations, catenary and current collectors,
- energy efficient solutions.

Increasing the power and speeds of trains requires the following:

- development of new types of catenaries for DC and AC supply,
- implementation of new solutions offering higher load capacity, reliability, serviceability, but lower vulnerability to weather (temperature, precipitation), theft and devastation,
- using proper tools, as MCA to undertake decisions about type of power supply to be used on newly constructed or modernized non-electrified lines, on which this paper is focused.

Multi-criteria analysis (MCA) is applied to wide area of problems, including transport systems issues, when an optimal variant needs to be selected from a defined number of variant solutions based on certain non-uniform criteria (de Oliveira et al.,2023;Grzeszczyk,2010;Jacyna et al.,2015; Taherdoost et al.,2023). Non-uniformity of criteria means that the transformation of criteria into a common set of grades is impossible, making straightforward comparisons difficult. Such criteria can include, for example, cost in euros, number of pieces, area, length in km, time units etc. or even rankings assessed by experts to determine how a specific variant meets the defined criterion.

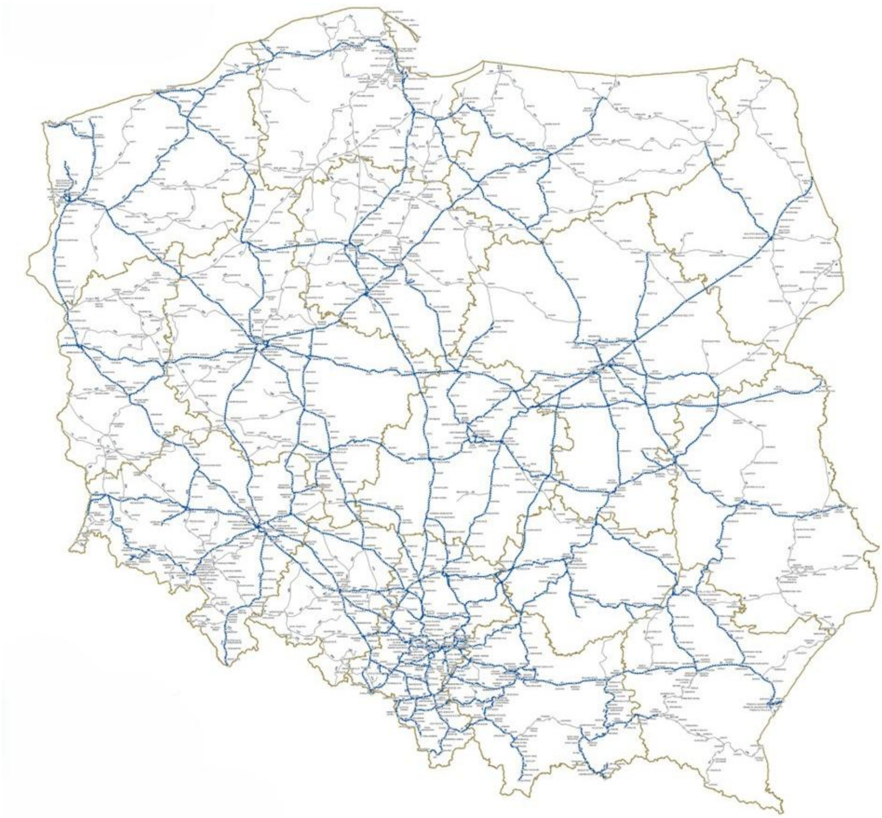

Fig. 1. Map of railway lines in Poland (blue lines - electrified ones, grey lines-non-electrified) - 2024 (source: (Burak-Romanowski,2025))

Multi-criteria analysis (MCA) makes it possible to take into account non-measurable outcomes, such as influence on the economy, development of industry, compatibility with the existing systems, environmental effects, even when conflicting qualitative and quantitative criteria are to be taken into account. So resulted from MCA multi-criteria decision making (MCDM) is based on such aspects.

In literature it could be found publications in which a special focus is made on application of MCA to energy problems. A wide range of literature review on MCDM application in energy management is presented in (de Oliveira et al.,2023;Lin et al.,2021). The idea and range of MCDM is introduced, and the MCDM methods used in the studies concerning energy systems are summarized and explained. Publications combining in energy management complex scenarios and multiple criteria are discussed. Several variables and factors as: energy efficiency, reliability of power supply, investment and maintenance costs in life-cycle are taken into account with application to the issues more refined methods as optimization methods, which helps to undertake various and complicated decisions with multiple criteria to consider. These papers have proved, that the MCDM is a feasible and currently applied method in energy systems. In (Nezhad et al.,2023) application of MCDM in optimization of Multi-objective energy system performance is presented. A comprehensive review on some well-known multi-objective optimization methods to the environmental issues, reliability of the system, energy losses, voltage security, and stability issues is discussed. Solving a multi-objective optimization problem would provide the decision maker with a variety of solutions, which are all optimal (Pareto optimal front), from which it is possible to choose the best fitting the criteria set by the decision-maker.

A wide review of methods in different stages of MCDM for sustainable energy, i.e., criteria selection, criteria weighting, evaluation, and final aggregation is presented in (Jiang-Jiang et al.,2009). The criteria of energy supply systems based on technical, economic, environmental and social aspects are summarized. Several methods based on weighted sum, priority setting, outranking, fuzzy set methodology and their combinations are employed for energy decision-making. Interesting observation is made in this paper, that the investment cost and CO_2 emissions are the most important ones in all evaluation criteria and that equal criteria weights are still the most popular weighting method, while analytical hierarchy process is the most popular comprehensive MCDA method.

In (Ling Zhang et al.,2015) assessment of clean energy resource options for the Jiangsu Province of China is discussed. The context of actual background information and evaluation methodology with critical techniques and key processes to assess evaluation criteria with application of MCDM method for clean energy resource alternatives.

A presentation of the developed multifactor multicriteria (MAMCA) methodology is shown (Schär et al., 2022) to involve stakeholders with different views and objectives (where qualitative and quantitative criteria are to be considered). It is also possible to develop simultaneously its own set of criteria and weights but also indicates compromise options when addressing complex social problems of energy systems during transitions to sustainable systems with renewable energy sources.

In (Siskos et al.,2022) MCDM is applied to problem of resilience of electrical energy power supply in different countries with ranking 35 European countries according to 17 interacting evaluation criteria. The paper aims to deliver guidelines and areas to improve resilience, which could help policymakers in the analysed countries.

However, there is a little publication concerning application of multicriteria analysis to power supply of railway infrastructure. In (Kljaić et al.,2023) is presented a review of literature and discussion of problems and new technologies which could support to undertake decisions toward making railway transport more energy efficient. In (Jefimowski et al.,20180 a method of supporting the decision-making process for implementation of a regenerative inverter in a 3 kV DC traction system is presented. The proposed method is composed of two steps. The first one is based on the solution of power flow problem in the novel model of DC power supply system with the limited overhead contact system receptivity. The second step consists in execution of an optimization-oriented procedure (based on genetic algorithm), which finally gave Pareto fronts, from which a single optimal solution could be found based on the assumed criterion.

The problem of improving existing railway station infrastructure for ecological transformation, including energy issues in discussed in (Nowotarski et al.,2024), where results of Eurail projects (Eurorail,2025) are taken into account. A study-case with focus on problem of reduction of energy costs and CO_2 emission by different types of trains is discussed in (Pomykala et al., 2022).

The novelty of the research presented in the paper is seen mainly in identification and scaling criteria for application in a multi-criteria analysis (MCA) to support undertaking decision (multi-criteria decision making -MCDM) which type of a power supply system 3 kV DC or 25 kV 50 Hz is optimal to be chosen on a specific railway line in an area of densely spread existing railway lines supplied by 3 kV DC system. 3 kV DC system is not recognized as to be developed for railways due to its power capacity limits and in countries when 3 kV DC system is used, as Italy or Spain new lines, specifically with speed above 250 km/h 2x25 kV 50 Hz system is proposed without any more profound analysis. So the proposed approach is really a new one, as there is no available in literature research on complex methods for undertaking decision based on detailed singling-out pros and contras in a comparable form for choosing 3 kV DC or 25 kV 50 Hz for a specific section of a railway line. Typically (Analysis of costs…,2006; Jaspers,2023) only CBA is applied in such cases, which, according to authors is not precise enough to have a complex description of all costs and problems which could appear during investment and operation processes of electrified line with a chosen power supply system. So, in a specific case of Polish railways, with 12150 km of electrified under 3 kV DC, without experience with 25 kV 50 Hz system such problem is a vital one, as in a CPK project (https://www.cpk.pl/en/, 2024) 1800 km of new or to be modernized non-electrified railway lines are to be electrified and justification of selection power supply system, based not only of simplified but more complex justification is a significant issue with taking into account many aspects, not taken into account till now. And as it is seen from the presented two examples, for a shorter and longer railway lines. In some cases, 3 kV DC power supply could still have some advantages, which could be presented in a in a resulted numerical form. Thanks to that the presented approach could be easily used to compare results of assessment for 3 kV DC and 25 kV 50 Hz power supply.

The structure of the presented research in the paper is as follow.

In the chapter 1 introduction to the problem of railway electrification, to which the paper is committed, is presented. A review of literature with research on MCA and MCDM applied to energy systems is discussed, taking into account the area of the paper and a novelty of the presented research is underlined. A classical approach to justification of undertaking decision about electrification of railway lines is shown in the chapter 2. Next specific character of railway power supply with underlining advantages and disadvantages of 3 kV DC and 25 kV 50 Hz systems is described in the chapter 3. The chapter 4 is committed to the proposed methodology, applied to assessment and choice of railway power supply, based on multi-criteria analysis (MCA). The economic and non-economic criteria for both 3 kV DC and 25 kV 50 Hz systems, which are taken into account, are presented in detail. Two examples of application of the proposed method to different railway lines are presented and discussed in this showing influence of the assumed weighted factors on the final results, which could support to undertake decisions of application 3 kV DC or 25 kV 50 Hz system based on many parameters characteristic for a specific railway line.

In the chapter 5 Conclusions the results of the presented research, its advantages and area of application are underlined and summarized.

2. Justification of railway lines electrification

Typical approach to decision-making on electrification of a railway lines is based on identifying what is called a trigger point (point 1 in Fig. 2), i.e. traffic volumes at which global costs of a diesel traction start to be higher than global costs of electric traction. It is typically reached at a high volume of traffic, as overhead costs of electrified railways (due to high expenditure on electric infrastructure) are much higher than for non-electrified railways, while variable costs of electrified railways fall with increasing traffic due to lower costs of energy (de Oliverira et al.,2023) and emission reduction (Pomykała et al.,2022). In assessing the need for electrification of particular line segment typically it seems absolutely necessary to cover essential operational factors in Cost-Benefit-Analysis. The following factors can be taken into account (Massel,2018):

- the number of trains operated on the segment,
- the number of trains running through from (or to) electrified part of the network,
- the passenger flows on the segment,
- the number of transfer connections from (or to) electrified part of the network,
- the typical time necessary for changing locomotive from electric to diesel one,
- the average time for passenger to change from diesel-operated train to the electric one (and v.v.),
- journey time difference (diesel traction versus electric traction) for all types of trains operated on the line segment and for all stopping patterns),
- existence of alternative routes (electrified, not electrified).

The next step in electrification decision-making is to choose a power supply system: either DC or AC. This choice depends on many factors, i.e.:

- nature of the line (agglomeration, sub-urban, intercity, high-speed),
- railway track characteristic (vertical and horizontal profile, presence of tunnels, viaducts and bridges),
- required transport capacity, category of traffic, types, masses and speeds of trains, which translates into demand for power,
- availability of public power grid in the vicinity of the line,
- effect on the environment (emissions of noise, land occupation, landscape) and technical infrastructure (EMC, stray currents, harmonics and the asymmetry caused in the supplying grid), safety (PN-EN 50163:2006; PN-EN 50-367:2021; PN EN 50122-2:2022; PN-EN 50388-1;2023; PN EN550122-1:2023;),
- the existing power supply system of the neighbouring railway lines to ensure compatibility,

or need for creating transition/separation zones (PN EN50122-3:2017).

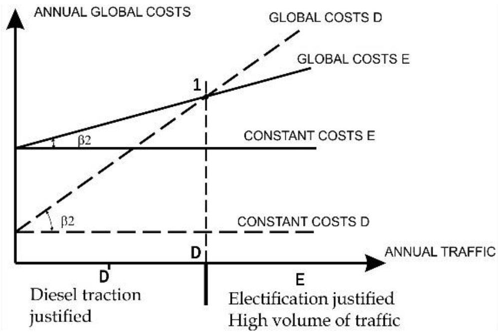

Fig. 2. Justification for electrification (1 - trigger point of electrification) – a typical approach, D-diesel traction, E- electric traction

3. Comparison of AC versus DC power supply systems

DC and AC railway power supply systems have their advantages and disadvantages to be carefully considered. Advantages of 3 kV DC:

- symmetry of 3-phase load on the AC side, lower power rating of traction substations, which makes it possible to supply them from a grid point.
- lower short-circuit power capacity,
- simpler supply system (bilateral, no phase-separation zones),
- smaller substations that are easier to build and occupy less land,
- higher reliability (bilateral supply, shorter sections that can be supplied by a single substation, so when a substation fails – shorter sections are out, smaller size of isolators (lower voltage than for AC),
- lack of inductive voltage drops and reactive power fluctuation at the traction side,
- no need to fit the phase to the supplying voltage during recuperation,
- lower overvoltages in the catenary,
- lighter rolling stock due to absence of an on-board transformer.

However, 3 kV DC systems have significant disadvantages:

- lower power supply capacity which limits the power rating of trains to
- 6÷8 MW and maximum speed to 250 km/h,
- harmonics at the AC side of substations due to rectifiers,
- large number of substations and points of connection to the grid,
- limited capacity to reuse the energy of recuperation,
- problems with clearing short circuits, and a need for high-speed breakers,
- high losses in the catenary due to high currents,
- heavy catenary with thick cross-section, high wear rate of the contact line,
- stray currents causing electro-corrosion,

Advantages of 25 kV 50 Hz systems:

- higher power capacity which allows for higher train speeds (regular service of trains up to 350-380 km/h),
- possibility of supplying longer catenary sections, so distances between substations could be longer than in the 3 kV DC system, so less substations and connections to the grid are needed,
- smaller cross-section of the catenary, lower wear rate of the catenary due to lower currents supplying the trains,
- lower losses in power supply lines and catenary,
- practically no problems with electro-corrosion,
- effective energy recuperation.

However, some disadvantages are observed:

- asymmetry in 3-phase supplying grid due to single-phase character of a traction load, resulting in a need to supply substations with high or very high voltage (with significant potential for short circuits) or install special transformers (Fig. 3) or static frequency converters (SFC),
- complicated systems of supply, with neutral and phase-separating zones,
- more land needed due to the footprint of traction substations larger than in 3 kV DC systems,
- larger isolation distances required,
- required solid earthing of the return catenary,
- inductive voltage drops, reactive power and resonances in the catenary, causing significant overvoltages,
- phase fitting needed during recuperation,
- a transformer required on-board of the rolling stock,

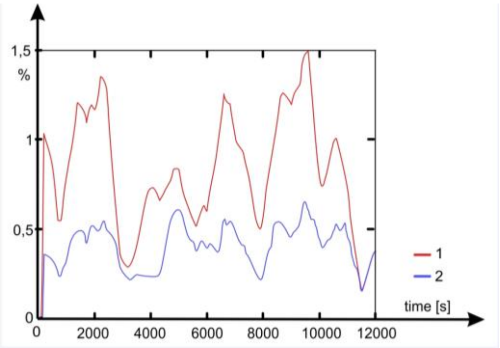

Fig. 3. Simulation results of averaged 10-min. asymmetry coefficient versus time caused in 110 kV grid by 2x25 kV 50 Hz traction substation -curve 1(red)- 2-phase transformer, curve 2 (blue) – V-V type special transformer installed in a traction substation to reduce asymmetry.

Therefore, the implementation of a new 25 kV 50 Hz system in Poland faces vital issues, such as:
- the need to use dual system rolling stock,
- lack of experience with the construction and operation of new 25 kV 50 Hz railway power supply,
- problems with parallel operation of more than 12150 km of 3 kV DC lines – transition zones; compatibility and safety issues between DC and AC railway power supply will be a hot issue,
- significant investments required in the public power grid.

All of the above-mentioned aspects are to be taken into consideration in choosing the power supply system for a specific line.

In (Commission Regulations 1299/2014 and 1301/2024), general requirements for railway traffic are provided, such as: maximum speed, types of trains, density of traffic, and power demand, as specified in the dedicated Standards (PN EN50122-3-2017; PN EN50122-3-2017; PN-EN 50-367:2021-06; PN EN 50122-2 –2022; PN-EN 50388-1: 2023–05; PN EN550122-1 2023–06; Technical Standards, 2022).

Consequently, the design of the railway power supply system must meet traffic requirements for the line, given that there are significant differences in traffic requirements for high-speed railway and for regional railways. Simulation tools are typically applied to make technical assessments of the proposed power supply infrastructure. An algorithm of functioning such a tool developed at Electric Traction Division of Warsaw University of Technology is presented in Fig. 4.

These methods have been used in study works, which in the range of design and analyses regarding ERL were of the 'feasibility study" type – and generally cover alternative solutions, with which to search the optimal one, in a sense of the best possible solution for the implementation, thus the compromise - in regard to the goal function. Another approach can rely on introduction of the notion of preference (utility function) assumed by a decision maker (lexicographic ordering). One can also add to the formulation of a utopian point (ideal solution), which serves as a point of reference for a set of obtained solutions, from which the point closest to the optimal (the best), in a sense of assumed criteria (standards) is selected. Thus, in case of ERL work study, one can talk about two aspects:
- defining the alternative solutions,
- comparative evaluation of the solutions

considered in relation to the results of simulation research conducted with usage of the developed ERL models for purposes of implementation of works.

In the process of preparation or modernization of ERL, each alternative solution takes into account that ERL is a complex system and that for the same structure different, possible to occur operation conditions of a line and schedules of individual transport flux and resulting power demands, which can greatly influence changes of the assumed values of the aim function can be adopted. On the other hand, while defining and estimating (assessment) the alternative solutions, it is taken into account that investments are made in the whole ERL system, which includes railway infrastructure (subsystems: rolling stock, command, signalling and traffic control, DC or AC supply system, power utility system). Therefore, the possible scenarios of the possible stages of activities in relation to the ERL in its technical-economic surroundings and environment, depending on the increase of demands for transport services with:
- increase of traffic flow,
- increase of speed,
- increase of trains' masses.

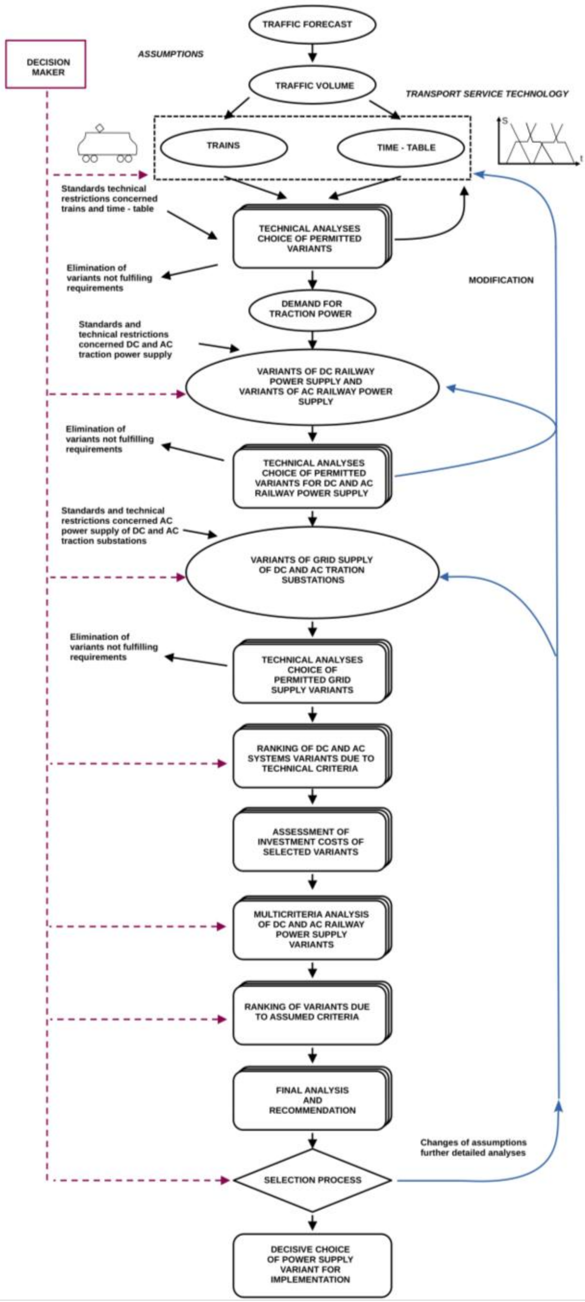

Fig. 4 An algorithm of a methodology of designing DC/AC power supply system of an electrified railway line (ERL) and application of multicriteria analysis MCA to undertake a decision of choosing the most appropriate one for a specific railway line and traffic.

As main data for analyses with usage of a package serve the demands for transport services resulting from a forecast, which implementation by ERL is treated as the main purpose. It is assumed that a transport forecast is given for each year. In order to accomplish transport, there is a rolling stock types, schedules are given. Then, we pre-define a set of variants of a DC and AC supply systems, which are possible for implementation, and which allow for a delivery of required by trains in service power and energy including technical restrictions. Subsequently, one defines schemes (variants) of an AC power engineering supply system provides a supply of required power to (according to the variant) AC or DC railway power supply with technical restrictions regarding grid. After performance of simulations, sets of solutions that do not fulfil the technical criteria are eliminated. For each solution, which meets transport and technical requirements, one calculates traction energy demands, costs of the solution implementation and exploitation costs.
In such a manner, due to the decomposition of an ERL system into subsystems, one obtains the sets of alternative solutions DC or AC power supply for the defined traffic flow.
Then, detailed simulation research concerning the selected, known as critical for the functioning of ERL elements of cooperation conditions of selected subsystems in a transient state (short-circuits, overvoltage's etc.) are being performed. Results of the conducted technical analyses complemented with a summary of costs, allow for the ranking of acceptable variants, according to the set technical criteria and a decision about whether or not to pursue with a given variant.
The results of simulations are next used in a further step of a comparison between DC and AC power supply with application of MCA (Fig. 4).

4. Multi-criteria analysis applied to railway energy systems

MCA as a decision-making aid is based on certain simplifying assumptions. First of all, dissecting an objective into particular criteria is a significant simplification, but it allows for effective problem solving by focusing on the most important features. Criteria are, as it were, partial objectives, the optimization of which allows for the best possible fit to the main objective. Solving complex tasks usually requires their description using a model defining the objective, a set of possible solutions, evaluation criteria and the function of the objective, evaluation of variants, and the selection rule. Such a model necessarily involves certain simplifications. The outcome of the analysis is the selection of a variant that is not worse, i.e. has higher scores based on the criteria, rather than unequivocally the best one. Therefore, it is necessary to know all the variants in order to choose the right one.
Reducing the criteria to a set of scores additionally allows for the assessment of complex problems using numerical values. The analysis should enable taking an optimal decision, i.e. selecting the variant that will bring the best expected outcomes for the decision-maker. It is necessary to strive for at least some of the criteria to be objective criteria, based on actual figures (investment costs, operating costs), and not only on expert assessment.
It should also be noted that any railway project is implemented in specific conditions. Some of them are fixed, i.e. cannot be changed (e.g. available financial resources, project location, assumed transport capacity, speeds, etc.). Flexible conditions, on the other hand, are self-limitations imposed independently by the decision-maker, which, unlike the fixed ones, can be somewhat changed in the decision-making process, depending on the outcome of the analysis. MCA is based primarily on the experience and knowledge of experts and decision-makers and their responsibility for the decision-making process. It should be remembered that multi-criteria analysis is only a tool to support, rather than to automate, decision-making.

4.1. Railway line power supply system variants

To support the selection of either the 3 kV DC or 2x25 kV AC power supply option for a new railway line, multi-criteria assessment can be made, using the criteria related only to the line power supply system in the 3 kV DC and 2x25 kV AC variants (Commission Regulation No 1301/2014; Massel,2018). Due to the limitations of power transmission capacity in the 3 kV DC system and the related power and speed restrictions (maximum train power of 6 MW and maximum speed of up to 200 km/h for passenger trains), the 3 kV DC system is rather suggested for P4 traffic category than for P2 according to according to TSI INF (Commission Regulation No 1299/2014). The 2x25 kV 50 Hz power supply system, due to its larger efficiency, can supply trains with a capacity of more than 6 MW, and may be used for all categories of traffic, however, P2 and P4 categories are taken into account in this paper as well.

4.2. Objectives and evaluation criteria

For the purposes of multi-criteria evaluation, two main objectives have been distinguished using the methodology of the procedure discussed in (Analysis of costs…,2006; Dean,2022; Jacyna,2001; Jacyna et al.,2015; Jaspers.2023; Jiang-Jiang Wang et al.,2009; Ling Zhang et al.,2015; Taherdoost et al.,2023), i.e. aggregated non-economic (technical, environmental) and economic objectives.

In each of the project implementation objectives, four (criteria group A) and five (criteria group B) (Table 1) basic objectives and criteria were identified, respectively, allowing for the parametric assessment of the possibility of achieving the objective in individual variants (Table 2).

In order to conduct multi-criteria evaluation, it was necessary to assign relative importance to the objectives and to the individual criteria. For the main project objectives, four scenarios of their relative importance were adopted. The importance (weights) of objectives according to individual scenarios is presented in Table 1. The weights of partial evaluation criteria were left the same across all analysed scenarios of the importance of project objectives. The partial criteria for individual objectives and their weights are presented in Table 2.

Table 1. Importance of project objectives

Group of criteria for the assessment of objectives		Weights, by scenario			
		I	II	III	IV
A	**Non-economic**	60%	50%	40%	30%
B	**Economic**	40%	50%	60%	70%

Table 2. Evaluation criteria and their relative importance.

	Criterion		
	No	**Name**	**% weight**
A-non-economic	A1	The level of advancement of technical and process solutions to ensure proper functioning in Polish conditions*	25
	A2	Time (ease) of implementation	25
	A3	Operational integration with existing 3 kV DC electrified lines	40
	A4	Readiness to implement technical solutions/meeting TSI requirements	10
B-Economic	B1	Time savings, possibility of increasing transport volumes	20
	B2	Impact on the economy (development of new technologies, increasing industrial potential)	10
	B3	Capital expenditure	25
	B4	Operating costs	30
	B5	Administrative procedures	15

*Note: all analyses leading to the selection of the variant must ensure the full level of safety required by regulations and standards. These analyses assume that the level of safety is absolutely ensured, and, on this basis, the selection is made based on the indicated criteria. Neither the time (ease) of implementation, readiness to implement technical solutions, time savings, investment outlays or procedures can have an impact on the degradation of the level of safety. Therefore, all aspects must be absolutely refined before further strategic stages concerning electrification in the AC system. Preparation for the above requires work at the decision-making stage, so that the implementation of the new system takes place in full awareness of its correctness and compatibility with existing systems. The described aspect has been included in Table 2 as criterion A.4 "Readiness to implement technical solutions" and its weight of 10% is unrelated to the non-negotiability of this issue (which must be achieved in 100%), but it only emphasises the need to carry out additional preparatory work, which will have to be performed despite the previously defined processes.

4.3. Principles of assigning scores to individual criteria. General assumptions

In order to assess a given variant from the point of view of a criterion, it is necessary to determine the value of that criterion. The objectives summarised in Table 1, as well as their criteria (Table 2) are quantitative (measurable - group B) and qualitative (unmeasurable - groups A and B). Consequently, to make all the criteria comparable, they were assigned a score. The score can range from 0 to 10 points. The following interpretation was adopted: if a given criterion receives score zero in a given variant, it means that it is the least favourable solution from the point of view of this criterion, while score 10 – the most favourable solution from the point of view of the analysed criterion.
The method of scoring for individual criteria was as follows: for measurable criteria, such as capital expenditure acc. to (Jiang-Jiang Wang et al.2009) one of the most important ones in assessment of energy systems) or operating costs, we aim to minimize the costs, i.e. the lower the costs, the higher the score (i.e. the variant with higher costs has a lower score, and the one with the lowest costs – 10), i.e. where it was possible to assign a numerical value to the criterion, the score of P_{Kmj} for the *j-th* variant was determined (calculated) by normalization according to the following formula:

$$P_{Kmi} = \left[1 - \frac{(K_{mi} - K_{mmin})}{K_{mmax}}\right] \cdot 10 \qquad (1)$$

where:
K_{mi} – value of the measurable criterion for the *i-th* variant, e.g. the cost of investments (traction substations, catenary, supplying lines), costs of traction substations connection to the grid resulted from installed power in substations, operational costs with annual energy consumption, power demand costs etc. for a given variant of AC and DC railway power supply),
K_{mmax} – maximum value of the measurable criterion,
K_{mmin} – minimum value of the measurable criterion,
For non-measurable criteria, the score was determined as the arithmetic mean of the score awarded by a team of experts appointed for this purpose according to the adopted assumptions (according to the adopted scale) or arbitrarily. Each of the experts could award from 0 to 10 points to each non-measurable criterion (thus determining their score) for individual variants.

4.4. Non-economic criteria

Non-economic criteria, due to a certain arbitrariness of their application, should take into account the conditions related to a specific line.

The level of advancement of technical and process solutions to ensure safety in Polish conditions-A1

For this criterion the important are: the impact of the advancement of technical solutions of a given system on its correct implementation due to the level of rated voltage, the occurrence of hazardous voltages, including the risk of potential exhalation, overvoltages, cooperation with the power system and impact on the environment (ensuring electromagnetic compatibility with other industries and third parties: stray currents, induced voltages and others EMC issues). For P4 lines (Commission Regulation No 1299/2014), due to the previously described requirements for the maximum train current (which are difficult to meet under 3 kV DC system and need oversizing the power supply system) and the requirement to implement new solutions, the 25 kV and 3 kV system should be treated equally.
The score of the criterion is arbitrarily adopted by experts,

Time (with delays caused by difficulties) of implementation-A2

The score of this criterion depends on the time needed to implement the investment for individual power supply variants resulting from the need (or no need) to expand the power system, the availability of power lines in the region to connect substations to, the possibility of using existing substations on contact lines, availability of equipment on the market (whether manufactured domestically or imported), the level of experience of designers and contractors in delivering similar projects. The criterion does not include the time needed for strategic analysis, risk analysis and mitigation necessary for the correct implementation of the new system while ensuring full level of railway safety (see the note under Table 2).

Table 3 presents the suggested scoring for a given variant depending on the local conditions for a given line.

Operational integration with existing electrified lines and rolling stock in a 3 kV DC system-A3
This criterion is related to operational compatibility with the existing 3 kV DC power supply system of railway lines, i.e. the possibility of using existing facilities (traction substations, section cabins) and the possibility of using the currently used single-system rolling stock on new lines (few multi-system vehicles are used, less than 5% of more than 3,000 pieces of single-system rolling stock powered by 3 kV DC), therefore, the shorter the new line, the higher the score of this criterion (it is unreasonable to power short lines with 25 kV and purchasing dual-system rolling stock adapted to 25 kV on short sections between 3 kV DC lines). For the 25 kV 50 Hz power supply variant, the proposed score for this criterion is zero.
The PKP PLK SA standards (Technical Standards,2022) impose very restrictive requirements on the power supply system for P2 lines (speed 200-250 km/h), including adaptation to traffic with trains consuming 4 kA, regardless of the power of the rolling stock the operator intends to use on the line. Therefore, for the 3 kV DC power supply system, the P4 criteria for the P4 type line (maximum speed up to 200 km/h) have been adopted, even though the assumed train with the highest power consumes up to 2.5 kA.

Degree of readiness for implementation of technical solutions-A4
Variants of supplying selected railway lines with the 2x25 kV 50 Hz system (which has not been used in Poland so far) along with the 3 kV DC system used in Poland, for which the equipment and devices have been manufactured in Poland for years (or even exclusively in Poland, such as rectifier units) are to be taken into account. At the end of 2024 y. 12,150 km of railway lines are electrified in the 3 kV DC system, powered by more than 470 substations. Since 2011, a program of intensive modernization of the 3 kV DC power supply system has been implemented with the support of EU funding, and by 2030 more than 70% of the power supply equipment will be modernized. Therefore, for the 3 kV DC system, it should be considered that the economy and railways are fully prepared to implement power supply on the new lines, provided that they are P4 lines (Commission Regulation No 1301/2014; Commission Regulation No 1299/2014; https://www.cpk.pl/en/, 2024;Technical Standards,2022). For P2 category lines, although it is possible to operate train and electric traction unit traffic (e.g. ED250) up to 250 km/h, the requirements of PKP PLK SA standards will be costly and difficult to meet.

Table 3. Suggestions for the assessment of variants from the point of view of the investment implementation time

Variant	Range of works	Time-to-delivery	Score
1	2	3	4
3 kV DC	Possibility of connection to the local substation or 110 kV line	Standard	0-5
2x25 kV	Difficulties in connecting to the HV network	Longer	0-5
Railway line type P2	25 kV AC.		5
Railway line type P4	25 kV AC.		5
Railway line type P4	3 kV DC		5

Table 4. Proposed scoring for individual variants of electrification of railway lines depending on the parameters of the line (total score is the sum of two subcriteria I and II)

Power supply variant	Length of line	Sub-criterion I (score)	Ratio of the number of existing 3 kV DC substations in use to the number of new 3 kV DC substations along the line	Sub criterion II (score)
3 kV DC (P4)	<80 km	4-5	>0,4	5
	(80-120>	3	<0,2; 0,4>	4
	(120-150> km	2	<0,1; 0,2)	3
	>150 km	1	<0;0,1)	1
25 kV 50 Hz (P2,P4)	For each line	5	For each line	0

On the other hand, for the 25 kV 50 Hz system, which has not been used in Poland so far, significant and long-lasting preparations are needed. There is a lack of experience, and the industry and the investor as well as the future infrastructure manager will have to prepare and pre-test new solutions. Procedural preparations will be needed related to the analysis of the risk and the method of reducing it to a level acceptable at the initial stages of decision-making on electrification with alternating current. Hence, the score for this criterion, taking into account only theoretical preliminary preparations, should be at 1-2.
Note: In the case of rigidly selected electrification variants, all of the above-mentioned aspects should be implemented earlier. In this case, the electrification of subsequent sections will already use the experience gained by the staff during the preparations for the electrification of the 25 kV line, which should improve the "readiness to implement technical solutions" for the analysed case. Due to the fact that the electrification date of individual sections has not been determined, each case will be treated independently, and experience from previous projects (e.g. those for which the 25 kV system has already been selected) will not be taken into account. The effect of experience on readiness can be taken into account after a few years from the commissioning of the AC-supplied railway line.

4.5. Economic criteria

Time savings, the possibility of increasing speed/transport volumes - B1

The scoring of the criterion of time saving and increasing the speed of transport for individual variants is presented below. The proposed values prefer the 3 kV DC system for shorter lines (if the P4 line category is adopted) with a small share of maximum speeds of 200 km/h or more, and, vice versa, where the sections of new lines are longer and the share of speeds of 200 km/h or more is higher, or the vertical profiles of the route are also larger, the 2x25 kV AC power supply variant is preferred. The alternating current system has greater power transmission capacity (power supply) to vehicles, and in the long term it enables an increase in speed to more than 250 km/h and should generally be used when selecting the P2 line category, hence for this category of line, the 25 kV system receives a additional 3 points (in total, each system cannot score more than 10 points).

Impact on the economy (development of new technologies, increasing the potential of industry)-B2

Using the 3 kV DC system for new lines is considered non-conductive to economic development as it has its limitations.
Due to the generally lower capacity of the powered trains, lower efficiency of energy supply, and speed restricted to 250 km/h, new lines built in this system should be of the P4 category, as lines in the P2 category impose high requirements on the power supply system. The introduction of the 25 kV 50 Hz system would provide a development stimulus for the industry to develop this technology after a period of mastering the solutions and their correct implementation on the domestic market, with opportunities to enter foreign markets. The score of this criterion can range from 0 to 10.
Note: For this to be possible, the opposite situation will first be necessary. The construction of AC system must be supported by the work of a team that has experience in its design and construction. Reverse verification is also preferred, i.e. by involving a second identical team, to verify and check all stages of design. Hence, it is advisable to import "know-how" first and export only in later stages.

Capital expenditure-B3

Capital expenditures in PLN thousand were assumed as a criterion based on estimated expenditures in individual cases in the 25 kV 50 Hz variant, which has not been used in Poland so far, and with similar designs under construction in Poland (for the 3 kV DC system). A connection fee resulting from the installed capacity in the substations supplying a given line has been added to the capital outlays. The proposed power supply variants ensure the supply of power and energy adequate to the assumed traffic. However, for the 3 kV DC power supply variant, an economical power supply variant was adopted, i.e. the movement of trains with lower power capacities, which means that the criteria for power consumption of 4 kA by a single train (required by the PKP PLK SA Standards for P2 category lines) will not be met because rolling stock with a maximum current consumption of 2.5 kA is adopted, ensuring the ability to drive at speeds of up to 250 km/h. It means that it will be necessary to obtain derogations from the requirements of (Technical Standards,2022) or an acceptance for category P4 lines.

Table 5. Proposed score values for individual variants of electrification of railway lines depending on the speed and profile of the line.

Power supply variant (type of traffic)	Length of section with speed Vmax>=200 km/h	Sub-criterion (score)	Ratio of length of section with Vmax>200 km/h to length of whole line	Sub-criterion (score)
3 kV DC (P4)	<80 km	5	>0,5	0
	(80-120>	3	<0,2; 0,5>	1
	(120-150> km	2	<0; 0,2)	2
	>150 km	1		
2x25 kV 50 Hz (P2,P4)	<80 km	2	>0,5	5
	(80-120>	3	<0,2; 0,5>	4
	(120-150> km	4	<0; 0,2)	1
	>150 km	5		

*Note, if the route is mountainous (there are profiles above 15 per mile on sections longer than 1 km), 2 points should be added to the 25 kV system, and if there are profiles above 25 per mile over a length of at least 500 m, 4 points should be added to the 25 kV system. If the score for this criterion exceeds ten points, it should be cut off at 10.

Table 6. Capital expenditure and scoring according to the formula (1)

Variant	Estimated capital expenditure	Score
1	2	3
3 kV DC		
25 kV 50 Hz		

Maintenance and operating costs-B4

The maintenance and operating costs of the line have been adopted in line with the EIB's recommendations, which define them as 1.5% of the pure capital expenditure of the individual options. Fees for the power ordered for substations on the line and the costs of traction and non-traction power of the line have been added to the annual operating costs.

The annual total maintenance and operating costs, calculated based on capital expenditures, are compiled in a table and then the score is determined according to formula (1).

Table 7. Operating costs and score for power supply variants (after standardization according to the formula (1)

Variant	Operating and maintenance costs	Score
1	2	3
3 kV DC		
25 kV AC.		

Administrative procedures-B5

The above criterion, considered in economic terms, was estimated based on the percentage relationship between the 3 kV DC power supply variant, which requires the construction of new 110 kV lines to supply the substation, and the 25 kV variant, for which the power supply with higher voltage lines is preferred. The above is associated with the need to conduct administrative procedures (including environmental ones, land occupation etc.), which are much more difficult in the case of lines with rated voltages of 220 kV or 400 kV. The problem when selecting the power supply system in the 3 kV DC variant will be to obtain the parameters required by (Technical Standards,2022) for P2 type lines, hence the 3 kV DC power supply system is proposed in the case of choosing the P4 category line for the line. It will also be important to define the type of investment – whether it is the construction of a new line or the modernization of an existing one.

Note: Power supply from the 110 kV level is possible with the use of solutions based on flexible improvement of network transmission capacity or reducing negative impact of AC system on public power grid. The last requires installation in AC traction substations costly symmetrizing devices or static phase converters. In this case, it will not result in a score for this criterion worse than in the 3 kV variant (110 kV power supply), but it will affect other technical and economic criteria for a given case.

5. Results of multi-criteria analysis

The scores awarded to each criterion for each of the analysed variants of railway line power supply should be summarized in Table 8.

The results of the multi-criteria assessment of the variants of the modernization of the considered line

carried out for four scenarios of the importance of the project objectives (Table 1) and importance of each criterion (Table 2) are presented in Table 9. As a result of this assessment, the recommended variant is selected.
A dedicated spreadsheet is used to determine the multi-criteria assessment indicators for each line marked as "subject to decision" regarding the selection of supply voltage (the algorithm is shown in Fig.4). Below are presented two examples of the assessment of new railway lines 40 km and 106 km long.

Table 8. Scores assigned to individual criteria for the analysed power supply variants of the line

No	**Power supply variant**	**PROJECT OBJECTIVES AND EVALUATION CRITERIA**			
		Non-economic (A)		**Economic (B)**	
		Criterion no	**Points**	**Criterion no**	**Points**
1	**2**	**3**	**4**	**5**	**6**
1.	3 kV DC	1		1	
		2		2	
		3		3	
		4		4	
		-		5	
2.	25 kV A.C.	1		1	
		2		2	
		3		3	
		4		4	
		-		5	

Table 9. Results of multi-criteria evaluation of the power supply variants for the railway line

Variant	**Variant evaluation for project objectives importance scenario**				**Score adjusted for the weights of the criteria for groups**			
					Group A		**Group B**	
	I	**II**	**III**	**IV**	**Criterion no.**	**Score**	**Criterion no.**	**Score**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
3 kV DC					1		1	
					2		2	
					3		3	
					4		4	
					-		5	
					Total score		**Total score**	
25 kV					1		1	
					2		2	
					3		3	
					4		4	
					-		5	
					Total score		**Total score**	

Example 1: Line about 41 km long (contact with a 3 kV DC powered line with the option to use existing 3 kV DC substations in the case of a 3 kV DC supply system. The results of the assessment are also presented in Fig. 5.

Table 10. Scores awarded to the criteria for the analysed line power supply variants

No	Power supply variant		PROJECT OBJECTIVES AND EVALUATION CRITERIA			
			Non-economic (A)		Economic (B)	
			Criterion no	Score	Criterion no	Score
1	2	3	4	5	6	7
1.	3 kV DC		A1	10	B1	8
			A2	5	B2	4
			A3	7	B3	10
			A4	10	B4	9.8
			-	-	B5	7
2.	25 kV AC		A1	3	B1	6
			A2	4	B2	10
			A3	0	B3	8,8
			A4	2	B4	10
			-	-	B5	9.2

Table 11. Results of multi-criteria evaluation of railway line power supply variants

Variant	Variant evaluation for project objectives importance scenario				Score adjusted for the weights of the criteria for groups Group A Group B			
	I (criteria B-40%)	II (criteria B-50%)	III (criteria B-60%)	IV (criteria B-70%)	Criterion no.	Score	Criterion no.	Score
1	2	3	4	5	6	7	8	9
3 kV DC	**7.93**	**8.02**	**8.11**	**8.21**	A1	**2.5**	B1	**1.6**
					A2	1.25	B2	0.4
					A3	2.8	B3	2.5
					A4	1	B4	2.94
					-		B5	1.05
					Total score	**7.55**	**Total score**	**8.49**
25 kV	**4.68**	**5.37**	**6.05**	**6.73**	A1	**0.75**	B1	**1.2**
					A2	1	B2	1
					A3	0	B3	2.3
					A4	0.2	B4	3
					-		B5	1.2
					Total score	**1.95**	**Total score**	**8.78**

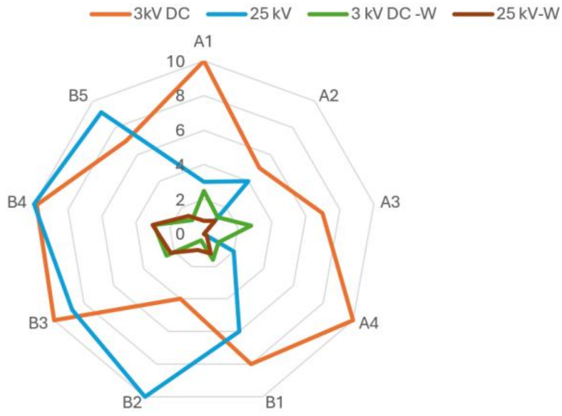

Fig. 5. Scores awarded according to the criteria for the analysed variants of power supply for the line (3 kV DC and 25 kV) set out in Table 8 and weighted by importance (Table 9) (3 kV DC-W and 25 kV-W)

The summary of the multi-criteria analysis results shows that, in each scenario, the 3 kV DC power supply variant is better, although in scenario IV, where the weight of economic criteria is the highest (70%), the difference in the assessment is the smallest. It has mainly resulted from the fact that the line is short and some of 3 kV DC traction substations from the existing infrastructure can be used.

In turn, the difference in price in favour of the 3 kV DC power supply variant is the largest when the weight of the economic criteria is the smallest.

Example 2: A 106 km line (contact with a 3 kV DC powered line which can use one existing 3 kV DC substation if a 3 kV DC supply system is chosen, or connection to the neighbouring 25 kV railway line-if 25 kV system is decided). The results of the assessment are also presented in Fig.6

Table 12. Scores awarded to the criteria for the analysed variants of power supply for the 106 km line

No	Power supply variant		PROJECT OBJECTIVES AND EVALUATION CRITERIA			
			Non-economic (A)		Economic (B)	
			Criterion no	Score	Criterion no	Score
1	2	3	4	5	6	7
1.	3 kV DC		A1	8	B1	6
			A2	5	B2	4
			A3	3	B3	10
			A4	10	B4	9.38
			-	-	B5	6
2.	25 kV AC		A1	8	B1	7
			A2	5	B2	10
			A3	3	B3	9.38
			A4	4	B4	10
			-	-	B5	8

Table 13. Results of multi-criteria evaluation of power supply variant for 106 km railway line

Variant	Variant evaluation for project objectives importance scenario I (criteria B-40%)	II (criteria B-50%)	III (criteria B-60%)	IV (criteria B-70%)	Score adjusted for the weights of the criteria for groups: Group A Criterion no.	Group A Score	Group B Criterion no.	Group B Score
1	2	3	4	5	6	7	8	9
3 kV DC	**7.02**	**7.16**	**7.29**	**7.42**	A1	2.0	B1	1.2
					A2	1.25	B2	0.4
					A3	0.75	B3	2.5
					A4	2.5	B4	2.81
					-		B5	0.9
					Total score	**6.5**	**Total score**	**7.81**
25 kV	**6.58**	**6.97**	**7.36**	**7.76**	A1	2.0	B1	1.4
					A2	1.25	B2	1
					A3	0.75	B3	2.34
					A4	1	B4	3
					-		B5	1.2
					Total score	**5.0**	**Total score**	**8.94**

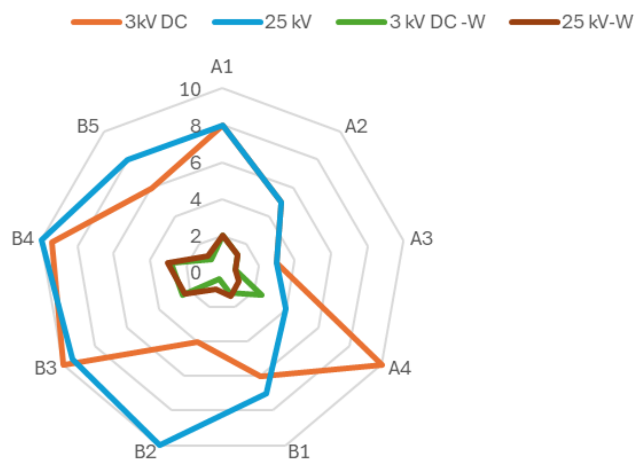

Fig 6. Scores awarded to the criteria for the analysed line power supply variants (3 kV DC and 25 kV) set out in Table 12 and weighted by importance (Table 13) (3 kV DC -W and 25 kV -W)

The summary of the multi-criteria analysis results (Table 13) shows that the scenarios with 3 kV DC power supply variants are better only when the weight of economic objectives is equal to (scenario II) or less than (scenario I) the weight of non-economic criteria. In scenarios III and IV, where the weight of the economic criteria is 60 or 70%, the 25 kV power supply system performs better. This is due to the fact that the section of the line is 106 km long and it is possible to use only one 3 kV DC traction substation from the existing infrastructure from one side of the designed line (if the 3 kV DC system is selected), but from the other end a 25 kV supplied line could be connected.

6. Conclusions

The novelty of the presented in the paper research is seen mainly in identification and scaling criteria for application in a multi-criteria analysis (MCA) to support undertaking decision which type of a power supply system 3 kV DC or 25 kV 50 Hz is to be chosen for a specific railway line in an area of densely spread existing railway lines supplied by 3 kV DC system. A review of available in the literature MCA applied in MCDM in area of energy systems is presented, when conflicting qualitative and quantitative criteria are to be taken into account. However, there is practically only a few papers in literature with such an approach to railway electrical energy aspects, which is a vital issue in countries with widely developed network of DC (3 kV or 1,5 kV) railway supply system, when significant investments are planned to electrify lines, with speeds up to 200-250 km/h interconnected with existing electrified lines being electrified under 3 kV DC.

The presented method allows us to obtain numerical results that provide a basis for decision-making on the selection of a power supply system, taking into account the specificity of the line placed in the railway system in Poland electrified under 3 kV DC voltage and advantages/disadvantages of each system if applied to a specific railway line.

3. The proposed concept of using MCA and MCDM to the evaluation of a 3 kV DC and 25 kV AC power supply systems takes into account various economic and non-economic criteria, which makes the method more reliable than only typical CBA. It is possible to make focus on different criteria by changes of weighting factors, according to the criteria importance, specific conditions of the line or policy of the decision-maker (Fig. 4).

The method can be adopted for decision support in selection of optimum power supply solution either in case of electrification of completely new railway lines (including high-speed lines), or in case of electrification of existing lines. Moreover, the similar approach can be used for analyses of investment in other systems of power supply (like 15 kV AC or 1.5 kV DC)

The proposed method of application of multi-criteria analysis for comparing DC and AC power supply systems is flexible and scalable, and can be fitted to meet other chosen criteria, including external costs of railway lines and different weights to underline superiority of some criteria.

The presented method of analysis could make a kind of support of the transformation of railway transport into competitive enough to fulfil the main points of sustainable development of societies with the Green Deal policy of the EU.

The shown analyses for typical cases of railway sections to be electrified showed, that operational aspects are particularly important. The results of MCA applied to two exemplary cases confirmed, that from operational point of view it is usually more effective to electrify short sections of line with 3 kV DC system due to compatibility of this line with the rest of the adjacent network and opportunity to use the existing one system DC rolling stock. On the other hand, it can be effective to electrify longer sections (over 100 km long) of new line with 25 kV AC power supply, particularly in a case of design speed higher than 200 km/h (P2 traffic category). For longer sections usually it is necessary to acquire completely new rolling stock (equipped for operation under 3kV and 25 kV catenary).

Due to strategic character of electrification of railway lines, in some cases the final decision may be based rather on political reasons than the presented criteria (which is underlined in Fig 4.). So, the MCA approach could make a strong backup to support justification of undertaking reasonable decisions.

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