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THE IMPACT OF ECONOMIC FACTORS ON THE MANAGEMENT OF THE STRUCTURE OF AN ENERGY-SELF-SUFFICIENT MINE WATER PUMPING STATION

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Purpose: The pumping stations owned by Spółka Restrukturyzacji Kopalń S.A. (SRK S.A.) pump approximately 100 million cubic metres of mine water per year. The pumping of this volume of water is associated with high electricity purchase costs. The process of pumping mine water must continue even after the mine has been closed. These pumping stations protect neighbouring mines and lower-lying areas from flooding and underground aquifers from contamination. Reducing pumping costs would reduce the company's need for budget subsidies. The aim of the research was to prepare a concept for the modernization of a mining groundwater pumping station, which could be implemented by operators of similar pumping stations scattered across post-mining areas.
Design/methodology/approach: The innovative energy self-sufficiency scenarios proposed in the article not only meet SRK S.A.'s needs, but also fit with Just Transition processes. Likely directions of change in design preferences with further potential changes in the economic situation have been indicated. The article draws the attention of designers to the need to forecast the market situation when designing new renewable energy installations.
Findings: Survey research and analysis of changes in selected market factors allowed us to learn about the susceptibility of preferences for choosing the designed renewable energy installations. The article analyses the impact of changes in the euro/zloty exchange rate, the unit cost of building a photovoltaic farm and the selling price of hydrogen on the preferences for choosing a variant of new self-sufficient energy installations.
Research limitations/implications: The study analyzed the influence of selected factors on design preferences of innovative technical and organizational systems that could be used in such capital-intensive activities as the protection of post-mining areas from flooding by constant drainage of water flowing from the rock mass to the workings of liquidated mines. It seems necessary to know the influence of other environmental factors on the possibility of modernizing existing mine water pumping stations.
Practical implications: The change in the preferences for selecting variants for individual evaluation criteria resulted in an increase or decrease in the absolute value of the analyzed factors, most often exceeding 15 percentage points.

Social implications: Mine water pumping stations protect the rock mass and the ground surface from flooding. Innovative development of post-industrial areas will allow for the creation of new jobs for retrained miners, and at the same time will be a source of drinking water and energy for the post-mining agglomeration.
Originality/value: The combination of the Just Transition problem and the need to dewater closed mines has not been the subject of comprehensive scientific research. The article proposes an innovative use of mine water pumping stations and adjacent post-industrial areas, which leads to improved economic efficiency of both issues.
Keywords: drainage of liquidated mines, multi-criteria analysis, renewable sources of energy, hydrogen extraction, revitalization of post-mining installations.
Category of the paper: Research paper.

1. Introduction

Just Transition in Silesia is similar to that in other regions that formerly based their local economy on the mining industry. Decision-makers preparing societies to achieve climate neutrality pose the challenge of post-mining regions to go through a difficult transformation process (Badakhshan et al., 2023; Barszczowska, 2023; Bondaruk et al., 2015; Chmielewska et al., 2020, Gupta, 2023b; Kaczmarek et al., 2022; Kaczmarek, 2022; Mostafa et al., 2024; Shavarskyi et al., 2022; Shnorhokian, Mitri, 2022; Talhofer, Hošková-Mayerová, 2019). Just Transition is also an opportunity for development for post-mining regions, the opportunity to invest in renewable energy sources and create new markets related to green energy and sustainable transport (Amoah, Stemn, 2021; Biały et al., 2020; Chmiela, 2023; Chmiela et al., 2023; Gajdzik et al., 2023; Gupta 2023a; Prusek, Turek, 2018; Riesgo Fernández et al., 2020). Just Transition in the Upper Silesian Coal Basin is also the opportunity to restructure and revitalize post-industrial areas remaining after previous intensive mining (Weijian et al., 2024; Wojtacha-Rychter et al., 2024a, 2024b; Seheda et al., 2024; Gasior et al., 2023; Smolinski, Howaniec, 2023; Siudyga et al., 2023; Pylypenko et al., 2023). The described variant of self-sufficiency energy project of the underground pump station is one of many elements that may affect the economic and social structure of one of the cities of the Silesian agglomeration and the entire region (Chmiela et al., 2023; Mhlongo, Amponsah-Dacosta, 2016; Mhlongo, 2023; Salom, Kivinen, 2020; Smoliło et al., 2023; Yousuf et al., 2023). Drainage of goafs from liquidated mines by SRK S.A. protects active coal mines against potential flooding. The company pumps out approximately 100 million m^3 of water annually using deep-well or stationary drainage methods (data for 2022). The purchase of electricity is one of the largest cost components (Łabaj et al., 2020; Janicka, Sajnóg, 2022; Mucha et al., 2016; Shavarskyi et al., 2022; Shnorhokian, Mitri, 2022; Wysocka et al., 2019). The main research goal was to learn the impact of changing economic conditions on design preferences when choosing a variant of the energy self-sufficiency project of an example of the underground pump station belonging to the Branch of SRK S.A. called Central Mine Drainage Plant in Czeladź (CZOK). In addition to cover the energy needs of the underground pump station, the project aims to revitalize its facilities, maintain the existing ones and create new jobs (Bondaruk et al., 2015; Gawęda, 2024; Panahi Borujeni, Gitinavard, 2021; Prakash Pandey, Prasad Mishra, 2022; Smoliło et al., 2023; Taha, Abdel-Wahab, 2024).

The analyzed underground pump station is located in one of the districts of a large city in the Silesian Agglomeration. Water is pumped into the nearby river in accordance with the water law permit. The surface facilities of the underground pump station are accompanied by a reclaimed area of 8.7 ha. In 2022, it pumped out 1.1 million m^3 of water. It is estimated that the underground pump station requires approximately 6.25 GWh of electricity to perform its activities.

2. Materials and methods

The calculations and design assumed the implementation of an installation producing energy for own needs. One way to reduce the demand for purchasing electricity from the grid is to build photovoltaic farms. When the system will provide electricity at night or on non-sunny days, it is necessary to use a system for storing the energy generated during sunny days (battery) (Chand, Paladino, 2023; Changqing, Jong-Beom, 2021; Doorga et al., 2022; Jae-Chan et al., 2021; Manowska, Nowrot, 2022). The project assumes the construction of a farm with a generating capacity of approximately 7.4 MWp, which will be able to produce approximately 10 GWh of "green", "clean" electricity annually. The peak of pump station requires approximately 2.3 MW of electricity. On sunny days, the demand will be completely satisfied by photovoltaic farm and then there will also be an overproduction of energy, which can be used during non-sunny periods after being "stored" (Słupik et al., 2021; Smoliński, Howaniec, 2020; Tokarski et al., 2021).

Insolation on sunny days meets more than the energy needs of the underground pump station. However, there is a need to store energy for non-sunny days. Storing energy in the produced hydrogen allows for very effective long-term storage of the generated energy surpluses and their use during greater demand for electricity (Gado et al., 2024; Howaniec et al., 2023; Wojtacha-Rychter et al., 2021; Zadrąg, Kniaziewicz, 2019). For these reasons, in two variants of the energy self-sufficiency project of the underground pump station, excess energy was assumed to be stored in hydrogen obtained in the electrolysis process, and battery storage was assumed only to power some devices operating also at night, to buffer the generated energy or for the possible needs of stabilizing the operation of electrolysers.

2.1. Analyzed variants of the self-sufficiency energy model of the underground pump stations. Adopted variants of modernization of the underground pump station

Assuming maximum use of the electricity that is generated, two groups of variants for the modernization of the underground pump station were designed. Each group comes in two types of variants, which gives four decision-making variants that differ in the amount of necessary expenditures and different degree of meeting the energy needs of the underground pump station. The first group of variants (variants 1 and 2) assumed only the construction of the so-called photovoltaic panel installation with the necessary equipment and infrastructure. In these variants, it will be necessary to obtain a license for electricity generation.

In the second group of variants (variants 3 and 4), obtaining a license for the production of electricity was abandoned in favor of storing energy in hydrogen obtained from electrolysis. This group of variants, apart from the installation of photovoltaic panels, includes additional equipment necessary for water electrolysis, storage, sale or combustion of the produced hydrogen.

2.1.1. Equipment and principle of functioning of variant 1 "Virtual prosumer"

Variant 1 assumes the implementation of an installation that produces energy for own needs on the basis of the so-called "Virtual prosumer". It is planned to build the installation of photovoltaic panels with the capacity of 6.89 MWp along with the necessary equipment and infrastructure. On non-sunny days, the underground pump station operates during periods of the day with the lowest electricity purchase price. It was assumed that the pumping time and operation of the most energy-intensive equipment would be changed to sunny periods with the farm's production. This change ensures the use of approximately 40% of the produced electricity in the underground pump station. The remaining surplus, i.e. approximately 60% of generated energy, will be transferred to the local supplier's network and at the same time collected to another underground pump station belonging to SRK S.A. This model requires payment of energy transmission costs to the local supplier.

2.1.2. Equipment and principle of functioning of variant 2 "Energy turnover"

Variant 2 assumes the implementation of an installation producing energy partially used for own needs. The surplus of energy produced will be sold to the network of the local "green" energy recipient. On non-sunny days, the underground pump station will operate during periods of the day with the lowest electricity purchase price. Income from the sale of surplus energy produced to another customer's network, and the income obtained will be used to purchase energy for the operation of the underground pump station during non-sunny periods. To simplify the settlement model, it was assumed that energy would be purchased from a local supplier in accordance with the currently negotiated price, and the excess production of "green" energy would be sold to a local customer for 80% of the negotiated purchase price of "black" energy.

2.1.3. Equipment and principle of functioning of variant 3 "Sale of hydrogen"

Variant 3 assumes storing of the excess generated by electricity in the form of hydrogen. In the period with excess production of electricity, the surplus will be stored in the form of hydrogen through electrolysis. The produced hydrogen, after being compressed to the rated value, will be transferred to the tank from where it will be sold on an ongoing basis at the refueling station at prices close to retail prices. The income obtained in this way could be used to purchase energy and work during sunny periods. Variant 3 requires additional equipment related to water electrolysis, hydrogen storage and distribution. Additionally, the sale of the produced oxygen will cover part of the costs of purchasing "black" energy for the submersible pumping station during non-sunny periods. Due to the fact that distribution costs are difficult to determine at this stage of design, it was assumed that the profit from hydrogen sales will be 60% of the current retail price.

2.1.4. Equipment and principle of functioning of variant 4 "Hydrogen combustion"

Variant 4 envisages storing of the excess generated by electricity produced by the photovoltaic farm in the form of hydrogen and then combusting it into cogeneration engines to obtain energy again. The cogeneration engines will produce electricity for the needs of the underground pump station, and the heat energy will be consumed for its own needs and transferred for a fee to the heating network of neighboring residential buildings. Any excess of hydrogen will be transported to another underground pump station to generate electricity and heat there. Variant 4, apart from the construction of the basic installation with photovoltaic panels with a capacity of 6.89 MWp along with the necessary equipment and infrastructure and a battery energy storage facility requires additional equipment related to water electrolysis, hydrogen storage and combustion.

3. Results and discussion

The conducted expert opinion research (Chmiela et al., 2023) showed that the criteria presented in Table 1 should be used to assess the liquidation model variant. The experts were scientific employees of scientific and research institutions and engineering and technical employees of the company's power machinery departments.

Table 1.
Criteria for assessing the underground pump station modernization options

Assesment criterion			Weight
1.	Reduction of expenses for electricity purchase	[financial units]	0.265
2.	Investment expenditures	[financial units]	0.269
3.	Energy independence of the company	[%]	0.354
4.	CO_2 emission	[Mg CO_2/rok]	0.052
5.	Workplaces	[items]	0.060

Source: Chmiela et al., 2023.

The variant was selected in two stages (Anton et al., 2019; Gossen et al., 2016; Gupta 2023a; Hudymáčová et al., 2010; Koziel, Pietrenko-Dabrowska, 2023; Stankevich, 2017; Wolnowska, Konicki, 2019). In the first stage of the evaluation, a single-criteria assessment was used for individual criteria and if more than one variant was selected, the variant with the smallest duration of time was finally selected. In the second stage, a multi-criteria analysis was carried out, taking into account all the criteria for assessing the analyzed four variants of the modernization of the underground pump station.

During previous research (Chmiela et al., 2023), it was found that the value of the currently negotiated purchase price of electricity has the greatest influence on the choice of variant in single- and multi-criteria assessment. To enable comparison of the impact of changes in the euro/zloty exchange rate, the unit cost of building a photovoltaic farm and the sales price of hydrogen on individual evaluation criteria and multi-criteria evaluation were analyzed for a constant value of the electricity price negotiated by the company in the third quarter of 2023.

In the analysis, the value of the analyzed factors (euro/zloty exchange rate, unit price of building a photovoltaic farm or hydrogen price) was changed in steps of 1 percentage point, looking for limit values that would cause a change in the classification of variants in a single- and multi-criteria assessment. The values estimated during the price research conducted in June 2023 were adopted as the base values of the analyzed factors. All information regarding costs (criterion "Reduction of expenses for electricity purchase" and "Investment expenditures") is provided in the adopted [financial units] expressed as a fraction of the base value, which is the amount of expenditures determined during the price research conducted in June 2023 for implementation of the first variant, called "Virtual prosumer". The simulated change in the euro exchange rate resulted in the change of three assessment criteria: "Reduction of expenses for electricity purchase", Investment expenditures" and "Energy independence of the company". The change in the unit costs of building a photovoltaic farm was reflected only in the level of criterion 2 "Investment expenditures". Due to the expected storage of surplus electricity in hydrogen obtained in the electrolysis process, the last factor analyzed was the price of hydrogen. The change in the price of hydrogen had an impact on the values of two evaluation criteria: "Reduction of expenses for electricity purchase" and "Energy independence of the company".

3.1. Changes in the value of criterion 1 "Reduction of expenses for electricity purchase"

To facilitate the analysis, a simplified method of calculating the value of criterion 1 "Reduction of expenses for electricity purchase" was adopted. It was assumed that the value of this criterion would consist of savings resulting from the actual current consumption of "green" electricity produced by the farm and from the use of stored surplus energy. This value should be increased by the income from the possible sale of "green" energy, sales of thermal energy, hydrogen or oxygen, and the costs related to their turnover should be reduced. The model assumes that any income obtained will be directed to the purchase of the missing "black" electricity from a local supplier at the currently negotiated rate.

Table 2.
Changes in the value of criterion 1 "Reduction of expenses for electricity purchase" caused by the change in the euro/zloty exchange rate

Euro/zloty exchange rate		-18%	±0.00	+17%
Variants		[financial units]		
1	"Virtual prosumer"	0.27	0.27	0.27
2	„Energy turnover"	0.28	0.28	0.28
3	„Hydrogen sale"	0.23	0.25	0.27
4	„Hydrogen combustion"	0.23	0.23	0.23
Score:		The best	The second	The third

Source: Author's own study.

The modeled change in the euro/zloty exchange rate resulted in the change of the value of reducing expenses for the purchase of electricity only for variant 3, which provides for the sale of obtained hydrogen (Table 2). The change in the euro/zloty exchange rate of 17 percentage points up and 18 percentage points down corresponded to the change in the criterion value of 8 percentage points up and down. Smaller changes in the euro exchange rate resulted in the change in the value of expenditures reduction without changing the order of classification of variants. Only the above-mentioned large changes in the euro exchange rate led to the correction of the classification of variants in the second and third positions. Regardless of the euro/zloty exchange rate, the best variant in this criterion for the negotiated purchase price of electricity in the third quarter of 2023 was variant 2 "Energy turnover".

Table 3.
Changes in the value of criterion 1 "Reduction of expenses for electricity purchase" caused by the change in the price of hydrogen

Hydrogen price		-15%	±0.00	+17%
Variants		[financial units]		
1	„Virtual prosumer"	0.27	0.27	0.27
2	„Energy turnover"	0.28	0.28	0.28
3	„Hydrogen sale"	0.23	0.25	0.27
4	„Hydrogen combustion"	0.23	0.23	0.23
Score:		The best	The second	The third

Source: Author's own study.

The analyzed change in the price of hydrogen, similarly to the change in the euro/zloty exchange rate, resulted in the change of the value of reducing expenses for the purchase of electricity only for the variant providing for the sale of obtained hydrogen (Table 3) and produced identical results. The only difference was the scope of changes introduced. The change in the price of hydrogen resulted in the change in the value of the reduction of expenses without changing the order of classification of variants, and only large increases in the price of hydrogen led to the correction of the classification of variants in the second and third positions, leaving variant 2 "Energy turnover" as the best. The reduction in the price of hydrogen by 15 percentage points and an increase in the price by 17 percentage points corresponded to the change in the criterion value of 8 percentage points up and down. For the conditions of the third quarter of 2023, in the criterion "Reduction of expenses for electricity purchase", the most favorable option was option 2 "Energy turnover", the next option was option 1 "Virtual prosumer", and the third option was option 3 "Hydrogen sale".

3.2. Changes in the value of criterion 2 "Investment expenditures".

When estimating the value of criterion 2 "Investment expenditures", fixed outlays for all variants were taken into account, such as outlays for the construction of a photovoltaic farm with full equipment (e.g. fencing, monitoring system, etc.) and operating costs (e.g. insurance, service costs, taxes, etc.) and costs related to additional equipment of the variants (e.g. direct power supply line for the local recipient, electrolysers, cogeneration engines, gas tanks, compressors and energy storage) along with their operating costs.

Table 4.
Changes in the value of criterion 2 "Investment expenditures" caused by changes in the euro/zloty exchange rate

Euro/zloty exchange rate		**-10%**	**±0.00**	**+10%**
Variants		**[financial units]**		
1	„Virtual prosumer"	1.00	1.00	1.00
2	„Energy turnover"	1.03	1.03	1.03
3	„Hydrogen sale"	2.63	2.74	2.86
4	„Hydrogen combustion"	2.95	3.06	3.18
	Score:	The best	The second	The third

Source: Author's own study.

The change in the euro/zloty exchange rate resulted in the change of the value of reducing expenses for the purchase of electricity only for variants 3 and 4, which provide for storing energy in the form of hydrogen (Table 4). For these variants, the change in the euro/zloty exchange rate by 10 percentage points up and down corresponded to the change in investment expenditures by 4 percentage points. Despite the change in the value of expense reduction, the order in which the variants were classified did not change.

Table 5.
Changes in the value of criterion 2 "Investment expenditures" caused by the change in the unit cost of building a photovoltaic farm

Unit cost of building a farm		**-10%**	**±0.00**	**+10%**
Variants		**[financial units]**		
1	„Virtual prosumer"	0.90	1.00	1.10
2	„Energy urnover"	0.93	1.03	1.13
3	„Hydrogen sale"	2.64	2.74	2.84
4	„Hydrogen combustion"	2.97	3.06	3.16
	Score:	The best	The second	The third

Source: Author's own study.

Table 5 shows the impact of changes in the unit cost of building a photovoltaic farm on investment expenditures. For variants 1 and 2, which do not provide for the storage of surplus electricity, such a change had a direct impact on modernization expenditures. Due to the additional components of variants of storing excess electricity in hydrogen, an example of a 10 percentage point change in the value of outlays down and up resulted in a change in capital outlays of 3 to 4 percentage points. For the conditions of the third quarter of 2023, the most favorable options were variants 1 "Virtual prosumer" and 2 "Energy turnover". Variant 3 "Hydrogen sale" was slightly worse.

3.3. Changes in the value of criterion 3 "Energy independence of the company"

In the adopted simplified method of calculating the value of criterion 3 "Energy independence of the company", the annual amount of electricity obtained by the photovoltaic installation of the underground pump station was divided by the annual energy demand of the company and expressed as a percentage.

An independently conducted analysis of changes in the euro/zloty exchange rate and changes in the price of hydrogen on the company's energy independence gave exactly the same results.

In both cases, the result was the change in the amount of energy obtained only for variant 3 "Hydrogen sale", which provides for the sale of obtained hydrogen (Table 6). The change in the euro/zloty exchange rate, as well as the downward price of hydrogen, by 15 percentage points corresponded to the reduction of meeting the company's demand by 7 percentage points and the promotion of variant 4 "Hydrogen combustion" to third place. Further reduction of the euro/zloty exchange rate and the price of hydrogen, despite the reduction of the company's energy independence, no longer resulted in changes in the classification of variants. When increasing the euro exchange rate and the price of hydrogen independently of each other, the limit was an increase in both factors by 31% percentage points. The result was an increase in the energy independence of the company for variant 3 "Hydrogen sale" by 14 percentage points and this variant moved to the second position from the third. Another limit value causing the change in the classification of variants was the increase in the euro/zloty exchange rate or the price of hydrogen by another 16 percentage points. With this value, for any of these factors, variant 3 "Hydrogen sale" turned out to be the best, ensuring the production of electricity providing 3.13% of the company's energy demand.

Table 6.
Changes in the value of criterion 3 "Energy independence of the company" caused by changes in the euro/zloty exchange rate or the price of hydrogen [%]

Euro/zloty exchange rate or hydrogen price		-15%	±0.00	+31%	+47%
1	„Virtual prosumer"	3.12%	3.12%	3.12%	3.12%
2	„Energy turnover"	2.93%	2.93%	2.93%	2.93%
3	„Hydrogen sale"	2.40%	2.57%	2.94%	3.13%
4	„Hydrogen combustion"	2.40%	2.40%	2.40%	2.40%

Score:	The best	The second	The third

Source: Author's own study.

In the case of the conditions of the third quarter of 2023, in criterion 3 “Energy independence of the company”, the most favorable was variant 1 “Virtual prosumer”, the next variant 2 “Energy turnover”, and the third variant 3 “Hydrogen sale”.

3.4. Changes in the value of criterion 4 “CO_2 emission”

The value of criterion 4 “CO_2 emission” adopted for the analysis depends only on the actual consumption of “green” electricity produced by the underground pump station's photovoltaic farm. Possible changes in the emission factor will not affect the order of selection of the underground pump station modernization variants adopted for analysis. The greatest emission reduction is characterized by variant 1 “Virtual prosumer”, followed by variant 4 “Hydrogen combustion”. The remaining variants are equivalent in this evaluation criterion and therefore, due to the lower duration of time, variant 2 “Energy turnover” was chosen.

3.5. Changes in the value of criterion 5 “Workplaces” resulting from changes in market conditions.

The estimated value of criterion 5 “Workplaces” is not dependent on changes in the analyzed market conditions. In this criterion, the best option is variant 4 “Hydrogen combustion”, the next option is variant 3 “Hydrogen sale”, and the third option is variant 1 “Virtual prosumer” due to the lower duration of time.

3.6. Multi-criteria evaluation of variants.

The multi-criteria evaluation of the adopted modernization variants of the underground pump station consists of obtaining a comprehensive assessment of the examined phenomenon, taking into account all the criteria for assessing the modernization variants (Chmiela, 2023; Chmiela et al., 2023; Smoliło et al., 2023). A standardized “OU” rating is assigned to criteria whose increase in absolute value is perceived positively in accordance with formula 1, while criteria whose increase in absolute value is perceived negatively is assigned a standardized assessment in accordance with formula 2. Each of the assessment criteria is assigned a weight affecting the result. The multi-criteria “OW” assessment was carried out according to formula 3.

$$OU_{ij} = \frac{h_{ij}}{h_{i\,max}} \tag{1}$$

$$OU_{ij} = \frac{h_{i\,min}}{h_{ij}} \tag{2}$$

$$OW_j = \sum_1^i w_i \cdot OU_{ij} \tag{3}$$

where:

OU_i - value of the normed assessment for the criterion „i” for variant „j”,

OW_j - value of the multi-criteria assessment for the variant „j”,

i - number of the criterion for assessing the pump station modernization options,

j - number of the underground pump station modernization variant,

w_i - weight for criterion number „i”,
$h_{i\ min}$ - the smallest value in criterion number „i”,
$h_{i\ max}$ - the highest value in criterion number „i”,
h_{ij} - value in criterion “i” for variant number “j”.

The ratio transformation method used in the multi-criteria assessment eliminates the problem of possible differences in the units of analyzed parameters and the difference in the absolute size of the numbers describing individual parameters by placing the obtained values of individual parameters as a dimensionless number in the range from 0 to 1 (Amoah, Stemn, 2021; Anton et al., 2019; Chmiela, 2023).

Table 7.
Changes in the value of multi-criteria assessment of the underground pump station modernization variants caused by changes in the euro/zloty exchange rate [dimensionless]

Euro/zloty exchange rate		-9%	±0.00	+10%
1	„Virtual prosumer”	0.9476	0.9476	0.9476
2	„Energy turnover”	0.8936	0.8936	0.8936
3	„Hydrogen sale”	0.6629	0.6807	0.7009
4	„Hydrogen combustion”	0.6636	0.6606	0.6574
	Score:	The best	The second	The third

Source: Author’s own study.

The modeled change in the euro/zloty exchange rate resulted in the change of the value of the multi-criteria assessment only for variants 3 and 4 with the storage of the obtained hydrogen (Table 7). The downward change in the euro/zloty exchange rate by 9 percentage points resulted in the change in positions 3 and 4 of variants 3 and 4. Regardless of the euro/zloty exchange rate, the best variant in the multi-criteria assessment for the realities of the third quarter of 2023 was variant 1 “Virtual prosumer”, and the next variant was variant 2 “Energy turnover”.

Table 8.
Changes in the value of multi-criteria assessment of the underground pump station modernization variants caused by changes in the price of hydrogen [dimensionless]

Hydrogen prices		-9%	±0.00	+10%
1	„Virtual prosumer”	0.9476	0.9476	0.9476
2	„Energy turnover”	0.8936	0.8936	0.8936
3	„Hydrogen sale”	0.6591	0.6807	0.7048
4	„Hydrogen combustion”	0.6606	0.6606	0.6606
	Score:	The best	The second	The third

Source: Author’s own study.

The change in the price of hydrogen resulted in the change in the value of the multi-criteria assessment only for variant 3 “Hydrogen sale” (Table 8). As in the case of the euro/zloty exchange rate, the downward change in the price of hydrogen by 9 percentage points resulted in the change in positions 3 and 4 of variants 3 and 4. For variant 3, the value of the multi-criteria assessment decreased by 3.2 percentage points, and the value of the multi-criteria assessment for the remaining variants were unchanged. Regardless of the hydrogen price, the best variant in the multi-criteria assessment for the realities of the third quarter of 2023 was variant 1 "Virtual prosumer", and the next variant was variant 2 "Energy turnover".

Table 9.
Changes in the value of multi-criteria assessment of the underground pump station modernization variants caused by changes in the unit cost of building a photovoltaic farm [dimensionless]

Unit cost of building a farm		-10%	±0.00	+10%
1	„Virtual prosumer"	0.9476	0.9476	0.9476
2	„Energy turnover"	0.8927	0.8936	0.8944
3	„Hydrogen sale"	0.6743	0.6807	0.6867
4	„Hydrogen combustion"	0.6545	0.6606	0.6662
	Score:	The best	The second	The third

Source: Author's own study.

The analyzed change in the unit cost of building a photovoltaic farm resulted in the change of the value of the multi-criteria assessment for variants 2, 3 and 4 (Table 9), and the value of the multi-criteria assessment of variant 1 "Virtual prosumer" was constant. Regardless of the amount of the unit cost of building a photovoltaic farm, the best variant in the multi-criteria assessment for the realities of the third quarter of 2023 was variant 1 "Virtual prosumer", the next variant 2 "Energy turnover" and the third variant 3 "Hydrogen sale".

The next step was to analyze the possible synergy in changes in these factors. Three hypothetical decision-making situations were modeled, including a joint change of all analyzed factors (tables 11, 12 and 13), which were compared with an unchanged decision-making situation (table 10), with a constant assumed purchase price of electricity negotiated by the company in the third quarter of 2023.

The first decision-making situation, called "Downgrading" (Table 11), is a situation in which all analyzed factors had their values reduced to a limit that changed the classification of variants. The euro/zloty exchange rate was reduced by 18 percentage points, the unit price of building a photovoltaic farm was reduced by 10 percentage points, and the price of hydrogen by 15 percentage points compared to the value from the third quarter of 2023. In this decision-making situation, the change in the multi-criteria assessment occurred only in variants 2 and 3. The modeled situation reduced the multi-criteria assessment of variant 2 "Energy turnover" by 0.1 percentage points and of variant 3 "Hydrogen sale" by 10.5 percentage points. As expected, there was the change in the classification of variants in position 3 and variant 4 changed places with variant 3.

In the second decision-making situation, called "Increase 1" (Table 12), all analyzed factors had their values increased to the first limit changing the classification of variants. The euro/zloty exchange rate was increased by 31 percentage points, the unit price of building a photovoltaic farm was increased by 10 percentage points, and the price of hydrogen by 31 percentage points compared to the value from the third quarter of 2023. Increasing the parameter values resulted in the change in the multi-criteria assessment of all variants without causing the expected change in their order. The modeled situation reduced the multi-criteria assessment of variants 1, 2 and 4. In variant 1 "Virtual prosumer" the assessment dropped by 7 percentage points, in variant 2 "Energy turnover" by 10.5 percentage points, and in variant 4 "Hydrogen combustion" by 8.9 percentage points. The multi-criteria assessment increased by 13 percentage points in variant 3 "Hydrogen sale". What is significant is the very quick reduction of the difference between the value of the multi-criteria assessment of variant 1 "Virtual prosumer" and the value of the multi-criteria assessment of variant 3 "Hydrogen sale".

In the third decision-making situation, called "Increase 2" (Table 13), all analyzed factors had their values increased to the first limit changing the classification of variants. The euro/zloty exchange rate was increased by another 16 percentage points (to 47), the unit price of building a photovoltaic farm was increased by another 10 percentage points (to 20), and the price of hydrogen by another 16 percentage points (to 47) compared to the value from the third quarter 2023. The subsequent increase in the values of the analyzed parameters again resulted in the change in the multi-criteria assessment of all variants, causing changes in their order. Variant 3 moved to position 2, and variant 2 dropped to position 3. The change in classification did not occur in position 1, where variant 1 remained, and in position 4 with variant 4.

Table 10.
Decision matrix for selecting the underground pump station modernization variant for the third quarter of 2023

		Lowering costs	Investment expenditures	Company's independece	CO_2 emission	Work-places	Multi-criteria evaluation
		[financial items]		[%]	[Mg CO_2/ year]	[items]	[dimensionless]
1.	„Virtual prosumer"	0.27	1.00	3.12%	7413	3	0.9476
2.	„Energy turnover"	0.28	1.03	2.93%	1832	3	0.8936
3.	„Hydrogen sale"	0.25	2.74	2.57%	1832	6	0.6807
4.	„Hydrogen combustion"	0.23	3.06	2.40%	3331	8	0.6606

Source: Author's own study.

Table 11.
Decision matrix for selecting the variant in the decision-making situation "Downgrade" (Euro exchange rate - 18%, Hydrogen - 15%, Construction cost - 10%)

		Lowering costs	Investment expenditures	Company's independece	CO_2 emission	Work-places	Multi-criteria evaluation
1.	„Virtual prosumer"	0.27	0.90	3.12%	7413	3	0.9476
2.	„Energy turnover"	0.28	0.93	2.93%	1832	3	0.8927
3.	„Hydrogen sale"	0.21	2.44	2.22%	1832	6	0.6091
4.	„Hydrogen combustion"	0.23	2.76	2.40%	3331	8	0.6606

Source: Author's own study.

Table 12.
Decision matrix for selecting the variant in the decision-making situation "Increase 1" (Euro exchange rate +31%, Hydrogen +31%, Construction cost +10%)

		Lowering costs	Investment expenditures	Company's independece	CO_2 emission	Workplaces	Multi-criteria evaluation
1.	„Virtual prosumer"	0.27	1.10	3.12%	7413	3	0.8810
2.	„Energy turnover"	0.28	1.13	2.93%	1832	3	0.8275
3.	„Hydrogen sale"	0.33	3.19	3.42%	1832	6	0.7695
4.	„Hydrogen combustion"	0.23	3.51	2.40%	3331	8	0.6021

Source: Author's own study.

Table 13.
Decision matrix for selecting the variant in the decision-making situation „Increase 2" (Euro exchange rate +47%, Hydrogen +47%, Construction cost +20%)

		Lowering costs	**Investment expenditures**	**Company's independece**	**CO_2 emission**	**Work-places**	**Multi-criteria evaluation**
1.	„Virtual prosumer"	0.27	1.10	3.12%	7413	3	0.8095
2.	„Energy turnover"	0.28	1.23	2.93%	1832	3	0.7575
3.	„Hydrogen sale"	0.38	3.47	3.94%	1832	6	0.7697
4.	„Hydrogen combustion"	0.23	3.79	2.40%	3331	8	0.5451

Score:	The best	The second	The third

Source: Author's own study.

In relation to the decision situation "Increase 1", the modeled situation "Increase 2" reduced the multi-criteria assessment of variant 1 by 7.5 percentage points, variant 2 by 7.8 percentage points and variant 4 by 8.6 percentage points. However, variant 3 slightly increased its rating by 0.1 percentage point. A further decrease in the difference in the value of multi-criteria assessments of variant 1 "Virtual prosumer" and variant 3 "Hydrogen sale" was observed. It should be assumed that further increases in the values of the assessed parameters could promote variant 3 "Hydrogen sale" into the optimal variant, but such large increases in the euro/zloty exchange rate, the unit price of building a photovoltaic farm or the price of hydrogen are unlikely.

Tables (12, 13, 14 and 15) serve as decision matrices based on which the decision-maker makes the final decision regarding the scope of modernization of the underground pump station. The decision matrices of hypothetical decision-making situations presented in Tables (13, 14 and 15) give the decision-maker a broader perspective with potential changes in market conditions. For the realities of the third quarter of 2023, in the multi-criteria assessment, the optimal variant was variant 1 “Virtual prosumer”, the next variant 4 “Hydrogen combustion”, and the third variant 3 “Hydrogen sale”.

4. Conclusions

The study analyzed the impact of changes in the euro/zloty exchange rate, the unit cost of building a photovoltaic farm and the price of hydrogen on individual evaluation criteria and the multi-criteria assessment of the energy self-sufficiency project of the underground pump station. To enable comparison of the impact of changes in these factors on individual assessment criteria and multi-criteria assessment, changes in the values of these factors were analyzed at the assumed constant price of electricity negotiated by the company in the third quarter of 2023.

The analyzed change in the euro exchange rate resulted in the change in the value of three evaluation criteria: “Reduction of expenses for electricity purchase”, “Investment expenditures” and “Energy independence of the company”. The change in the unit costs of building a photovoltaic farm was reflected only in the level of criterion 2 “Investment expenditures”. The change in the price of hydrogen resulted in a change in the value of two evaluation criteria adopted for the analysis: “Reduction of expenses for electricity purchase” and “Energy independence of the company”. The change in preferences for selecting variants for individual evaluation criteria resulted in the increase or decrease in the absolute value of the analyzed factors, most often exceeding 15 percentage points.

The lowest investment cost for the modernization of the underground pump station is provided for variant 1 “Virtual prosumer” and variant 2 “Energy turnover”. Variant 3 “Hydrogen sale” and variant 4 “Hydrogen combustion” require two or three times higher expenditures, but offer a much higher reduction in electricity bills. Variants 3 and 4, which provide for the storage of surplus energy generated in the form of hydrogen, ensure a much higher satisfaction of the underground pump station's energy needs, and their implementation is less dependent on external factors.

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