energies

Article

Hydrogen Storage and Combustion for Blackout Protection of Mine Water Pumping Stations

Andrzej Chmiela [1], Paweł Wrona [2], Małgorzata Magdziarczyk [3], Ronghou Liu [4], Le Zhang [5] and Adam Smolinski [6,*]

[1] Mines Restructuring Company (Spółka Restrukturyzacji Kopalń S.A.), 41-914 Bytom, Poland; achmiela@srk.com.pl
[2] Department of Safety Engineering, Silesian University of Technology, 44-100 Gliwice, Poland; pawel.wrona@polsl.pl
[3] Faculty of Economics and Management, Opole University of Technology, 45-758 Opole, Poland; m.magdziarczyk@po.edu.pl
[4] Biomass Energy Engineering Research Centre, School of Agriculture and Biology, Shanghai Jiao Tong University (SJTU), 800 Dongchuan Road, Shanghai 200240, China; liurhou@sjtu.edu.cn
[5] Department of Resources and Environment, School of Agriculture and Biology, Shanghai Jiao Tong University (SJTU), 800 Dongchuan Road, Shanghai 200240, China; zhle@sjtu.edu.cn
[6] Central Mining Institute, 40-166 Katowice, Poland
* Correspondence: smolin@gig.katowice.pl

Abstract: Global warming increases the risk of power outages. Mine water pumping stations pump approximately 100 million m^3 of water per year (2023). The cessation of mine water pumping would expose neighboring mines and lower lying areas to flooding. The pumping stations have some containment, but a prolonged shutdown could cause environmental problems. Remediation of the resulting damage would be costly and time-consuming. The combination of the problems of dewatering abandoned mines and storing energy in the form of hydrogen to ensure continuity of power supply to pumping stations has not been the subject of extensive scientific research. The purpose of this paper was to develop options for protecting mine water pumping stations against the "blackout" phenomenon and to assess their investment relevance. Six technically feasible options for the modernization of mine water pumping stations were designed and analyzed in the study. All pumping station modernization options include storage of the generated energy in the form of green hydrogen. For Q1 2024 conditions, the option with the partial retail sale of the produced hydrogen and the increased volume of produced water for treatment is recommended for implementation.

Keywords: drainage of liquidated mines; energy storage; renewable energy sources; hydrogen extraction; revitalization of post-mining installations

Citation: Chmiela, A.; Wrona, P.; Magdziarczyk, M.; Liu, R.; Zhang, L.; Smolinski, A. Hydrogen Storage and Combustion for Blackout Protection of Mine Water Pumping Stations. *Energies* **2024**, *17*, 2357. https://doi.org/10.3390/en17102357

Academic Editor: Manoj Khandelwal

Received: 23 April 2024
Revised: 7 May 2024
Accepted: 9 May 2024
Published: 14 May 2024

1. Introduction

The European Union (EU) has adopted policies to ensure that it achieves climate neutrality by 2050. One of the priorities is to move away from burning fossil fuels, including coal, and to produce energy from renewable energy sources (RESs). Poland is currently making a number of investments in renewable energy [1,2]. Until these investments are fruitful, coal will be the main fuel. In 2023, coal will generate almost 63% of all electricity in Poland (about 105 TWh). The term "blackout" is used to describe a sudden and severe failure of the power system, resulting in a loss of electricity over a large area. Usually, a blackout is understood as a prolonged power outage, even for several days [3,4]. The main causes of blackouts are as follows:

– Extreme weather events (sudden downpours, gusty winds, or hot weather);
– Overloading of the power grid;
– Lack of energy resources in the market;

– Human error;
– Armed conflict and terrorism.

The current level of security of electricity supply is satisfactory, but the first prolonged blackouts could occur as early as 2025. Problems could be caused by an aging power grid as old coal-fired power plants begin to be liquidated [5,6]. Spółka Restrukturyzacji Kopalń S.A. (SRK S.A.—Mines Restructuring Company, Bytom, Poland), which carries out liquidation and post-liquidation activities at former coal mine sites in Poland, aims to reduce negative environmental externalities as much as possible [7,8]. One way to reduce the impact is to generate energy from RESs [9–11]. The use of RESs depends on weather conditions, which poses many challenges [12,13]. On sunny days, the company's energy needs are met by photovoltaic farms. During the period of electricity production at SRK S.A., it will be possible to use only a part of the generated electricity [14,15]. Thus, the rest of the generated energy will be surplus that can be stored. In case of a blackout, it will be possible to use the previously stored energy, and the effect of energy security will be to increase the independence of the pumping station from external power supplies. The combination of the problems of ensuring the continuity of power supply to pumping stations by storing excess energy from renewable energy sources is a novel issue, and, to the authors' knowledge, no wider scientific research has been conducted in this area. The problem of ensuring the continuity of the goaf dewatering processes of abandoned mines and their economic efficiency is a universal problem of all abandoned mines, regardless of their location in the world [16,17].

In Poland, Spółka Restrukturyzacji Kopalń S.A. (SRK S.A.—Mines Restructuring Company) has been carrying out liquidation and post-closure activities at coal mines in liquidation for almost 25 years. One of the company's goals is to reduce the budget for statutory activities. This goal is accompanied by efforts to reduce the negative impact on the environment and to ensure a fair transformation of mining regions [18,19]. Mine water pumping stations have the greatest impact on the environment. The role of pumping stations is to protect nearby active mines and the land surface from flooding [20,21]. In addition to taking flooded areas out of service, the existing drinking water supplies available to the local community may be contaminated [22,23]. This is especially true given the increasing shortage of clean water in a densely populated region such as Upper Silesia. Annually, about 100 million m^3 (in 2023) of mineralized water is pumped from the goafs of abandoned mines. In some pumping stations, it is possible to selectively pump water from different former mine levels [24,25]. Typically, water mineralization increases with depth. In most cases, water produced from shallower levels requires only a small number of treatment processes [11,26,27]. All pumped water is discharged into local watercourses. This involves the release of a salt load into the environment. The pumping of water requires a significant amount of energy. In 2023, the demand for purchased electricity will be about 300 GWh. An additional problem is the emission of greenhouse gases into the atmosphere during barium desalination [28,29]. All of these conditions are compounded by the threat of blackout [30,31]. Mine water pumping stations have some retention, and a short-term blackout would not significantly affect safety risks. However, a prolonged "blackout" could cause disasters that would be difficult, lengthy, and costly to remedy [7,8]. For these reasons, SRK S.A. intends to undertake investment activities to ensure that all of the above objectives are met to the greatest extent possible.

The mine water pumping stations under discussion have the greatest potential for implementation of modernization measures [32,33]. In accordance with the guidelines of the European Commission within the framework of the European Green Deal and in Regulation (EU) 2021/1119, the European Climate Law, the modernization of pumping stations is being considered. For at least the partial coverage of the energy demand, the use of renewable energy sources (RESs) is envisaged, including photovoltaic farms with energy storage adapted to the needs of pumping stations [34–36]. The considerations presented in this article also apply to the broader aspect of using the existing mine shafts. Work is underway around the world to store energy in the shafts of abandoned mines, and this form of blackout protection for pumping stations could also be used [6,37]. Blackout protection of a remaining abandoned mine shaft could also be important from the perspective of other so-called green technologies such as carbon capture and storage (CCS) [31,38,39]. The use of RESs will reduce the carbon footprint of the process of draining water from the goaf of abandoned mines [40,41].

2. Materials and Methods

The pumping station for which the study was conducted is located in a large city in the Silesian Agglomeration (Poland). The pumping station is located in the facilities of a liquidated mine. Approximately 9 million m^3 of water is discharged annually into the local river, of which 2.5 million m^3 is low-mineralized water. Pumping is carried out 24 h a day, but with all pumps, it is possible to pump out incoming water for 18 h. For safety reasons, the main fans run continuously. To carry out the dewatering processes, 3.7 MW of equipment has been installed, and the energy demand of the pumping station reaches 33 GWh per year. The primary power supply is purchased energy from the national grid. Next to the buildings adapted for the pumping station is the site of the former main plant of the liquidated mine. The available land allows the construction of a photovoltaic farm with a capacity of about 13 MWp (0.13 km^2). The connections of the water and district heating networks are located within a few hundred meters from the boundaries of the properties adjacent to the pumping station.

In order to achieve the task of making the mine water pumping station as blackout resistant as possible, the pumping station was designed to be equipped with a photovoltaic plant, a Mine Water Treatment Station (MWTS), and a hydrogen extraction, storage, and combustion plant. In selecting the size of photovoltaic farms for all variants, the maximum available area of the former main plant of the liquidated mine was assumed. The use of RESs (photovoltaic farms) will reduce the energy demand of the pumping station, reduce the need for a budget subsidy, and reduce the equivalent CO_2 emissions into the atmosphere. The installed photovoltaic system will generate more energy than the pumping station and could be used on an ongoing basis. In this case, there will be a surplus of usable energy. The stored surplus will secure the continuity of power supply to the pumping station. In all variants, it was envisaged the generated surplus electricity will not return to the national grid, which made the application for a license to generate and distribute electricity unnecessary. In the upgraded pumping station, photovoltaic panels and power consumers are located on the same property. The electricity consumers are infrastructure related to mine water pumping. The largest consumers are the pumping systems and the main ventilation systems [42,43]. In order to buffer the power supply of the pumping station equipment operation with energy obtained from the photovoltaic farm, additional development of battery energy storage with a capacity of 2.5 MWh is envisaged. In an ideal situation, operating electrolyzers, in addition to power supply, require about 9 dm^3 of water to obtain 1 kg of hydrogen. In practice, the water requirement of electrolyzers reaches 20 dm^3 of water per 1 kg of hydrogen [12,40]. To reduce the cost of purchasing water for the electrolysis process at the analyzed pumping station, the construction of a Mine Water Treatment Station (MWTS) was planned. The size of the MWTS is adjusted to the volume of 2.5 million m^3 of low-mineralized water, the treatment of which is economically justified [44,45]. To increase the volume of low-mineralized water treatment, an optional intake was designed to treat rainwater discharged from photovoltaic panels. This will provide an additional volume of about 0.5 million m^3 of water. In addition to the construction of the basic installation from photovoltaic panels with the necessary equipment and infrastructure and the MWTS, additional equipment related to water electrolysis, hydrogen storage, and combustion will be required. The additional equipment consists of electrolyzers, hydrogen and oxygen compressors, cogeneration engines, oxygen and hydrogen storage tanks, and thermal energy storage. In all variants, the excess electricity generated in the electrolysis process will be converted into hydrogen. The stored hydrogen in times of energy shortage is to be directed to cogeneration engines to generate electricity for the pumping station's own needs. The processes of water electrolysis and cogeneration combustion are processes associated with the incidental production of thermal energy. Therefore, the construction of an underground thermal energy storage facility providing "own" heat is planned [46,47]. The thermal energy derived from the electrolysis and compression of the generated hydrogen will be utilized for the pumping station's own requirements, including the preheating of the expanded hydrogen prior to further processing. Any excess energy can be transferred to the heating of adjoining residential buildings. In the electrolysis process, a oxygen is also produced. It was planned to sell oxygen wholesale on the local market for 60% of its retail value. Revenues generated from the sale of treated water and oxygen, as well as thermal energy, will be used to purchase the missing portion of electricity, again reducing the need for a budget subsidy [30,48]. The conceptual diagram of the decision options for upgrading the pumping station is shown in Figure 1.

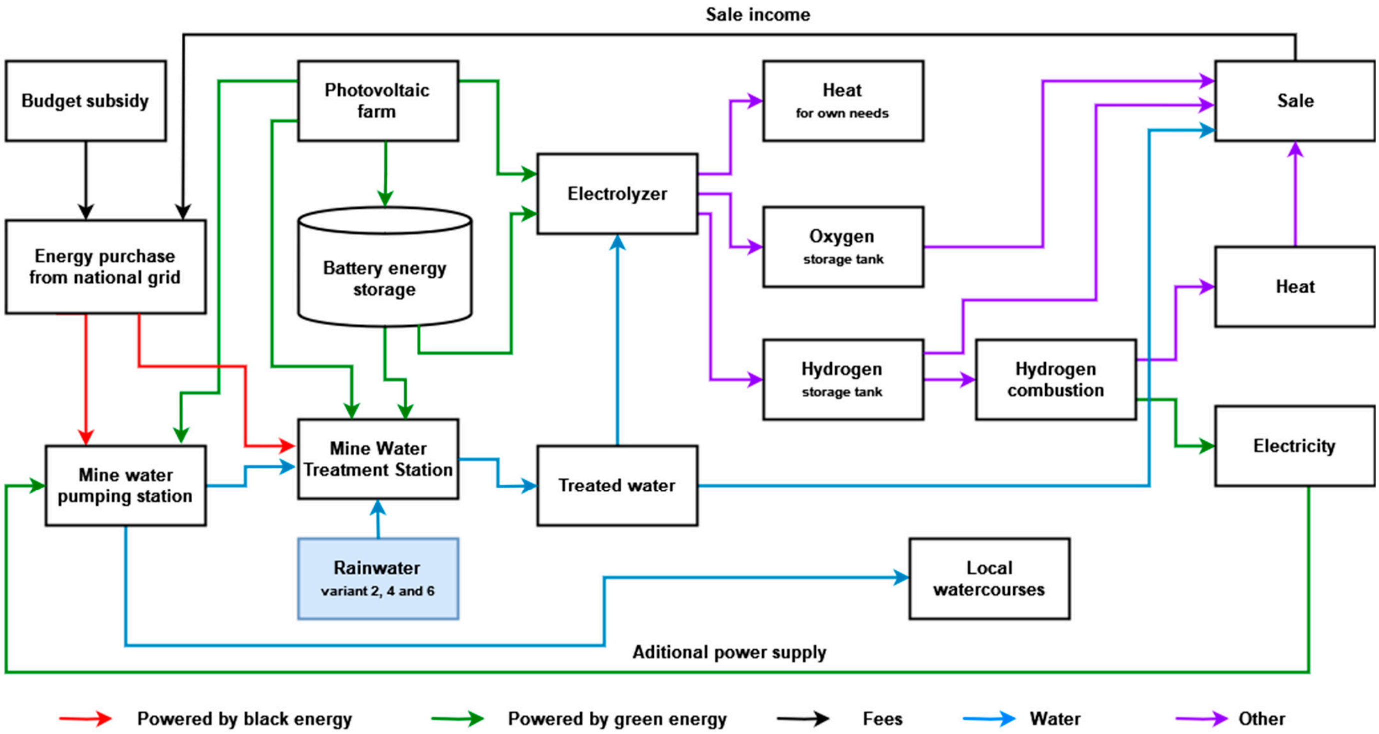

Figure 1. Schematic diagram of decision-making options for pumping station upgrades.

In terms of security of energy supply and self-sufficiency, with the assumption of maximizing safety against blackout phenomena, two groups of variants were designed for modernization of underground water pumping stations [22,27,49,50]. Variants 1 and 2 assumed combustion of all generated hydrogen, while variants 3, 4, 5, and 6 assumed storage and eventual combustion of only a part of the generated hydrogen. Unburned surplus hydrogen would be sold at wholesale prices to a local distributor or retail prices at the company's own vehicle refueling station. Due to the amount of water to be treated, two groups of variants were also designed. In variants 1, 3, and 5, only low-mineralized water pumped from the goaf is to be treated, while in variants 2, 4, and 6, rainwater captured from photovoltaic panels is also to be treated. The designed variants have a similar surplus of generated electricity, so the amount of hydrogen generated by the variants is similar [36,51,52]. Variants 2, 4, and 6 achieved an annual production of 222 Mg of hydrogen, and variants 1, 3, and 5 an annual production equal to 224 Mg of hydrogen.

In the study, six decision variants were designed, differing in the amount of necessary expenditures and varying degrees of satisfaction of security against the "blackout" phenomenon, as well as securing financial needs for the purchase of electricity for the pumping stations.

The research was conducted in three stages. The first stage included a study of the available literature and market discernment of the possible purchase of the necessary equipment and provision of services. The market discernment was conducted in Q1 2024, and the remaining calculation parameters were selected for this period. All monetary values were converted to the purchase of electricity in Q1 2024 and expressed in MWh. In the second stage, decision scenarios were designed for pumping station upgrades aimed at maximizing resilience to a long-term power outage from the national grid, the so-called "backout". The technical equipment, functional layout, and scope of operation of the designed decision variants were consulted on an ongoing basis with the managers of the company's power generation departments. On an ongoing basis, the designed variants were corrected for the purpose of obtaining properly functioning technical and organizational systems aimed at achieving the greatest possible resistance to the "blackout" phenomenon. Variants were also optimized for other functional parameters, but their importance was no longer a priority. In the final stage, the designed variants were subjected to single criterion analysis due to the most important parameters, and then, a global evaluation was carried out covering all parameters [53,54].

The single criterion analysis and global assessment allowed assigning specific variants the most suitable conditions for their application in practice. The prepared base of variants will allow the future decision-maker to more easily decide to implement the selected variant or create another one that is a hybrid of the designed ones [55,56].

The combined issues of environmental protection, energy efficiency, water treatment, and protection against power outages from the national grid for mine water pumping plants have not yet been the subject of wider scientific research.

3. Results and Discussion

3.1. Variant 1 and 2 with Full Combustion of Stored Hydrogen

In variants 1 and 2, the excess electricity produced by the photovoltaic farm will be stored in the form of hydrogen and fully developed on-site for its own energy needs (Figure 1). The technical equipment of both variants is similar. The difference lies in the use in Variant 2 of an additional installation for capturing rainwater from the photovoltaic panels. The installation will supply the MWTS with an additional volume of water that can be economically treated. Both variants are expected to create about three jobs for the company's relocated employees [51,56]. The obtained financial and environmental parameters of variants 1 and 2 of the pumping station modernization for the conditions of Q1 2024 are included in Table 1. When evaluating the financial parameters, the values expressed in money were converted to the purchase of electricity for the negotiated unit price in Q1 2024 and expressed in MWh.

Table 1. Financial and environmental parameters of variants 1 and 2 of the pumping station upgrade for Q1 2024.

	Unit\Variant	Variant 1	Variant 2
Total expenditures	[MWh]	269,021	270,610
Additional annual cost of maintaining the pumping station	[MWh]	1030	1133
Additional annual employee cost	[MWh]	930	930
Annual reduction in energy costs	[MWh]	−26,125	−24,978
Reimbursement of expenses	[years]	-	-
Reducing the carbon footprint	[Mg CO_2/year]	7524	7591
Autoconsumption of energy	[%]	26.75%	26.99%
Financial security for energy purchases	[%]	18.80%	22.22%
Energy security coverage	[%]	45.55%	49.21%
Self-powered hydrogen supply	[h]	828	821
Hydrogen supply purchased	[h]	242	305
Total hydrogen supply in emergency mode	[h]	1070	1127
Operation independent of external power supply	[h]/[days]	2670/111	2727/114

The pumping station can operate in its primary mode and in its emergency mode. In the primary mode, the operating photovoltaic farm will power the pumping station equipment. Buffering of power supply and stabilization of pumping station equipment operation with energy obtained from the photovoltaic farm will be achieved by a system of battery energy storage with a capacity of 2.5 MWh. The selected battery energy storage system is designed to provide a buffer for the operation of pumping station equipment and renewable energy sources (RESs). It should be noted that a direct connection of RESs with pumping station equipment may not always be technically feasible. This is of particular significance when the photovoltaic farm generates residual energy (for example, following sunrise or during periods of partial cloud cover). It is only after the storage of these small portions of energy and the subsequent acquisition of a sufficient amount that it will be possible to power the pumping station equipment with generated electricity. Furthermore, battery energy storage can be employed as an alternative source of electricity, for instance, for lighting at night. During periods with overproduction of electricity, its surplus will be directed to electrolyzers producing hydrogen and oxygen. The produced gases, after being compressed to their rated value, will be transferred to tanks. Oxygen will be sold at wholesale prices to a local distributor on an ongoing basis, while hydrogen will await periods of energy shortage at the pumping station. During non-solar periods, the hydrogen will drive cogeneration engines that produce electricity for the pumping station's own use. In order to protect the pumping station from the "blackout" phenomenon, it is assumed that a hydrogen reserve will be permanently stored in the hydrogen tanks to ensure, independent of external power supply, continuous operation of the cogeneration engines for 5 days. The generated electricity and heat will be consumed for own use, and the surplus heat energy can be given to the local operator's district heating network for a fee [30,53].

The purchase of electricity from a local supplier will be made in accordance with the currently negotiated unit power purchase price. The revenue from the sale of produced oxygen and thermal energy, as well as treated water at the MWTS, will enable additional financing of the purchase of electricity from the local supplier. This will enable additional financial coverage of about 18% of the pumping station's energy needs in Variant 1 and about 22% in Variant 2 (Table 1).

In emergency situations at another pumping station, hydrogen can be transported there to generate electricity and heat [26,35,57]. When the national grid runs out of power and information is obtained that the failure will drag on, the pumping station will go into an emergency operation mode. Activation of such a mode means disconnecting the pumping station from the national grid and implementing the procedure for operation in the so-called island system. As in the basic mode, during sunny periods the working photovoltaic farm will power the pumping station equipment, and the generated surplus will be converted into hydrogen. When electricity production from the farm is not sufficient to power the pumping station, cogeneration engines will be activated. Thanks to the hydrogen reserve in the storage tanks, it will be possible to operate the pumping station in emergency mode for at least 5 days. The revenue generated from the sale of produced oxygen and thermal energy, as well as treated water at the MWTS, will be an additional source of financing for the purchase of hydrogen from a local supplier. This will allow for extended island operation of about 240 to 300 h (Table 1). It will also be possible to obtain hydrogen from the resources of another pumping station not covered by the "blackout" phenomenon, which would further extend the possible operation time of the pumping station in emergency mode.

3.2. Variants 3 and 4—With Wholesale of Hydrogen

The process of electrolysis of water and the process of burning hydrogen are characterized by low energy efficiency [43,52]. It is estimated that, with the combination of these processes, it will be possible to use about 35% to 40% of the generated surplus "green" energy. For this reason, Variants 3 and 4 of the pumping station upgrade were proposed

(Figure 1). In both variants, the burning of the produced hydrogen in its entirety was abandoned in favor of selling it at wholesale prices to a local customer. The sale of hydrogen will be a form of virtual storage of electricity in the form of cash. For safety reasons in the face of the "blackout" phenomenon, only a smaller hydrogen storage facility is planned to be installed. This will slightly lower the capital expenditure. The storage facility would hold the hydrogen reserve necessary to supply the pumping station for 5 days, as well as the volume of hydrogen resulting from the technical conditions for distribution of hydrogen temporarily stored on-site. Additional equipment for the technical and organizational system of the modernized pumping station would be a wholesale hydrogen distribution facility. As in Variants 1 and 2, the difference between Variants 3 and 4 is the use in Variant 4 of an additional installation for capturing rainwater from photovoltaic panels. Both variants are expected to create about three jobs for employees relocated from other divisions of the company [32,57]. The basic parameters of Variants 3 and 4 for the conditions of Q1 2024 are presented in Table 2.

Table 2. Financial and environmental parameters of Variants 3 and 4 of the pumping station upgrade for Q1 2024.

	Unit\Variant	**Variant 3**	**Variant 4**
Total expenditures	[MWh]	268,703	270,292
Additional annual cost of maintaining the pumping station	[MWh]	1030	1133
Additional annual employee cost	[MWh]	930	930
Annual reduction in energy costs	[MWh]	17,986	19,095
Reimbursement of expenses	[years]	14.9	14.2
Reducing the carbon footprint	[Mg CO_2/year]	5137	5224
Autoconsumption of energy	[%]	18.26%	18.57%
Financial security for energy purchases	[%]	40.26%	43.50%
Energy security coverage	[%]	58.53%	62.08%
Self-powered hydrogen supply	[h]	120	120
Hydrogen supply purchased	[h]	619	678
Hydrogen supply	[h]	739	798
Operation independent of external power supply	[h]/[days]	2339/97	2398/100

The proposed technical and organizational layout of the modernized pumping station can operate in primary mode and in emergency mode. As in Variants 1 and 2, in the primary mode during sunny periods, the pumping station equipment will be powered by an operating photovoltaic farm. A system of battery storage (2.5 MWh) of energy will stabilize the operation of pumping station equipment powered by energy obtained from the photovoltaic farm. During non-sunny periods, it is envisaged that energy will be purchased from a local supplier with proceeds from the advance sale of surplus "green" hydrogen, treated water, and oxygen. The purchase of energy from the local supplier will be made according to the currently negotiated electricity purchase price. Surplus "green" electricity will be directed to electrolyzers that produce hydrogen and oxygen. The produced gases, after being compressed to their rated value, will be transferred to storage tanks. Oxygen and partially hydrogen on an ongoing basis will be sold at wholesale prices to a local distributor. The remainder of the hydrogen (a reserve for 5 days of operation) will await a possible power outage from the national grid, the so-called "blackout". In the basic mode of operation of the pumping station, the energy efficiency model assumes a mechanism of maximum consumption of the produced "green" energy for own purposes and sale of the produced gases to the local distributor at wholesale prices. Due to the cost of supplying oxygen and hydrogen, which is difficult to determine at this stage of design, it was assumed that the gases would be sold for 60% of the current retail price, and the treated water for 45% of the current retail price. The revenue from the sale of hydrogen produced in baseload operation, as well as oxygen and treated water at the MWTS, will enable additional financing for the purchase of electricity from a local supplier [5,34]. The purchase will be conducted in accordance with the currently negotiated unit power purchase price. This will enable additional financial coverage of about 40% of the pumping station's energy needs in Variant 3 and about 43% in Variant 4 (Table 2). In an emergency situation, at another pumping station, the stored hydrogen can be transported there to power it.

When informed that a "blackout" phenomenon has occurred, the pumping station will enter an emergency operation mode. In the emergency operation mode, the "island" operation procedure will be activated. After disconnection from the national grid, during periods of sunshine, the operating photovoltaic farm will power the pumping station equipment, and the generated surplus will be converted into hydrogen. All the hydrogen produced will be stored for the pumping station's own purposes. During non-sunny times, the operating procedure of cogeneration engines generating electricity and heat for own purposes will be started. During the first period, the hydrogen reserve stored in tanks and hydrogen that has not yet been sold will be used. Revenue from the sale of hydrogen produced in the primary mode of operation, as well as oxygen and treated water at the MWTS, will enable additional financing for the purchase of hydrogen from a local supplier [48,54]. The purchase of hydrogen from a local distributor will be carried out at 100% of the current retail price. This will allow additional supply to the pumping station for approximately 600 h in Option 3 and for 680 h in Option 4 (Table 2). The possible procurement of hydrogen from the resources of another pumping station not covered by the "blackout" phenomenon will further extend the pumping station's emergency operation time.

3.3. Variants 5 and 6—With Retail Sales of Hydrogen

In order to reduce the financial losses resulting from the difference between the wholesale and retail prices of hydrogen [5,48], as a result of the study, another two variants for upgrading the pumping station were proposed, Variants 5 and 6. These variants are a development of Variants 3 and 4. In these variants, the hydrogen produced is to be sold to the local community at prices close to retail prices. Additional equipment for the upgraded pumping station consists of hydrogen compressors of H35 or H70 standard (necessary for refueling hydrogen vehicles) and a hydrogen refueling station. Due to the cost of hydrogen supply, which is difficult to determine at this stage of design, it has been assumed that sales will be made at 90% of the current retail price. It is envisaged to leave a hydrogen reserve in the tanks allowing uninterrupted power supply to cogeneration engines for 5 days. The investment in the construction of an in-house hydrogen refueling station will increase capital expenditure. As in the variants presented earlier, the difference between Variants 5 and 6 lies in the use in Variant 6 of an additional installation for capturing rainwater from photovoltaic panels. Both variants are expected to create about four jobs for employees relocated from other divisions of the company [43,56]. The increase in employment is due to the need to provide services to the hydrogen refueling station around the clock on all days of the year. The basic parameters of Variants 5 and 6 for the conditions of Q1 2024 are presented in Table 3.

The operation of the technical and organizational system of such a modernized pumping station in both primary and emergency modes will be analogous to Variants 3 and 4. As in the previous variants, the sale of oxygen and treated water to local distributors at wholesale prices will be carried out. Due to the cost of oxygen supply, which is difficult to determine at this stage of design, it has been assumed that oxygen will be sold at 60% of its current retail price, and treated water at 45% of its current retail price. By increasing the disposal price of hydrogen and using the revenue from the sale of oxygen and treated water, it will be possible to develop a much larger financial reserve for the purchase of electricity or hydrogen. In the primary mode of operation of the pumping station to supply equipment during non-sunny periods, the financial reserve will allow for the additional purchase of about 54% of the pumping station's energy needs in Variant 5 and about 57% in Variant 6 (Table 3). In the emergency mode, revenue from the sale of hydrogen produced in the primary mode, as well as oxygen and treated water, will enable the purchase of hydrogen from a local supplier. As in Options 3 and 4, the purchase of hydrogen from a local distributor will be conducted at 100% of the current retail price. This will allow additional supply to the pumping station for approximately 990 h in Variant 5 and for 1045 h in Variant 4 (Table 3). The possible acquisition of hydrogen from the resources of another pumping station will further extend the pumping station's emergency operation time.

Table 3. Financial and environmental parameters of Variants 5 and 6 of the pumping station upgrade for Q1 2024.

	Unit\Variant	Variant 5	Variant 6
Total expenditures	[MWh]	282,051	283,640
Additional annual cost of maintaining the pumping station	[MWh]	1030	1133
Additional annual employee cost	[MWh]	1239	1239
Annual reduction in energy costs	[MWh]	22,354	23,374
Reimbursement of expenses	[years]	12,6	12,1
Reducing the carbon footprint	[Mg CO_2/year]	5137	5224
Autoconsumption of energy	[%]	18.26%	18.57%
Financial security for energy purchases	[%]	53.81%	56.93%
Energy security coverage	[%]	72.07%	75.51%
Self-powered hydrogen supply	[h]	120	120
Hydrogen supply purchased	[h]	867	925
Hydrogen supply	[h]	987	1045
Operation independent of external power supply	[h]/[days]	2587/108	2645/110

3.4. Variants' Analysis

The designed decision variants for upgrading the pumping station are characterized by different technical, utility, or economic parameters [45,49]. The parameters of the designed variants were adopted according to the price discernment conducted in January 2024. The adopted forecast is valid for the conditions of the first quarter of 2024 (Q1 2024). The obtained financial and environmental parameters of the pumping station modernization variants for Q1 2024 conditions are included in Tables 1–6. The values of the financial parameters expressed in money were converted to the purchase of electricity for the negotiated unit price in Q1 2024 and expressed in MWh. Any subsequent price changes will change the calculated parameters. With a possible change in market conditions, one should not count on a qualitative change in the obtained parameters. Therefore, the analysis carried out in the future can be a reference for investment decisions [18,19]. However, this decision should be made based on a number of different factors such as economic, technical, utility, environmental, etc. [42,46].

When evaluating pumping station modernization options in terms of safety against the occurrence of the "blackout" phenomenon, it is important to consider the operation time of the pumping station independent of the external power supply, i.e., the ability for so-called "island" operation. In island operation mode, due to the safety of repair crews removing the "blackout" phenomenon, connections to the national grid are interrupted. In the decision variants analyzed, the power supply comes from an operating photovoltaic farm or from the combustion of stored hydrogen [1,2]. The photovoltaic farm was assumed to operate for 1600 h per year, which is the average value for the Upper Silesia region. During non-sunny periods, an emergency operation mode will be activated. The equipment will be powered by electricity obtained from the combustion of stored hydrogen, followed by hydrogen purchased from an earned financial reserve obtained from the sale of treated water, hydrogen, oxygen, and possibly heat. The reserve is worked out during periods when the pumping station is operating in its primary mode. A number of factors may influence the proposed outsourcing, including the availability of hydrogen, its price, and other considerations. It is proposed that an in-house storage facility will serve as the primary source of hydrogen for cogeneration engines. The in-house stock should be sufficient to maintain the uninterrupted operation of the pumping station for a period of five days. In the event of an emergency, a possible incidental purchase of small quantities of hydrogen will be conducted. In such a scenario, financial considerations will be of secondary importance.

As the first criterion for evaluating the variants, the minimum operating time of the pumping station was used when supplying hydrogen obtained and stored on-site [23,37,39]. In the criterion "Self-supply of hydrogen", Variants 1 and 2, which provide for burning the entire volume of hydrogen, are the most favorable (Table 4). With the hydrogen generated, the pumping station can operate for 35 or 34 days (828 and 821 h), respectively. In the other variants, according to the design assumptions, the hydrogen reserve, depending on the momentary filling, allows the pumping station to operate continuously for at least 5 days (120 h).

Table 4. Analysis of the possibility of emergency operation of the pumping station independent of external power supply for the reality of Q1 2024.

	Unit\Variant	**1**	**2**	**3**	**4**	**5**	**6**
Self-powered hydrogen supply	[h]	828	821	120	120	120	120
Hydrogen supply purchased	[h]	242	305	619	678	867	925
Supply of own and purchased hydrogen	[h]	1070	1127	739	798	987	1045
Operation independent of external power supply	[h]	2670	2727	2339	2398	2587	2645
	Result:	Best		Second		Third	

Once the hydrogen in the company's own tanks has been used up for continued emergency operation, it will be necessary to purchase hydrogen from a local distributor for the financial reserve previously developed. The largest reserve is generated by variants that provide for the sale of hydrogen. For this reason, in the criterion "Purchased hydrogen supply", the most favorable variants are 6, 5, 4, and 3, respectively. Purchased hydrogen, in the most favorable variant 6, will allow uninterrupted operation of the pumping station powered by hydrogen combustion for up to 39 days (925 h).

The last two evaluation criteria are "Supply of own and purchased hydrogen" and "Operation independent of external supply". These criteria are similar to each other and give the same results. In both criteria, the maximum operating time of the pumping station in emergency mode when supplied with hydrogen (own and purchased) is evaluated, and in the "Operation independent of external power supply" criterion, this value is increased by the maximum operating time of the pumping station supplied with energy generated by a photovoltaic farm [3,4]. In both criteria, Variants 1 and 2, which provide for the combustion of all the hydrogen produced, are the most favorable. They obtained uninterrupted operation for 45 and 47 days (1070 and 1127 h), respectively, in the criterion "Supply with own and purchased hydrogen", and 111 and 114 days (2670 and 2727 h) in the criterion "Operation independent of external power supply". The equipment of all variants is similar; therefore, the maximum emergency operation time for the other variants in the criterion "Supply with own and purchased hydrogen" was also similar, ranging from 31 to 44 days (739 to 1045 h), and in the criterion "Operation independent of external power supply", from 97 to 110 days (2339 to 2645 h). If the only evaluation criterion was the duration of protection against the "blackout" phenomenon in the reality of Q1 2024, the most favorable variants would be Variants 1 and 2.

The technical equipment of all variants is similar, which makes the necessary expenditures for their implementation similar. The difference between the cheapest and most expensive variant is only 5.6%. When evaluating variants for modernization of pumping stations safe from the "blackout" phenomenon, variants 3, 1, 4, and 2 (Table 5) required the least financial outlays in turn. Two of them provide for wholesale of the generated hydrogen. On the other hand, the highest investment was recorded in Variants 6 and 5, which assume retail sales of hydrogen. The highest result is due to the investment in the company's own vehicle refueling station. The annual additional cost of maintaining the pumping station is also similar. The additional installation of rainwater harvesting from photovoltaic panels only slightly increases the capital expenditure, as well as the additional cost of maintaining the pumping station [25,50]. The highest additional employee costs again occurred in Variants 5 and 6 (Table 5), in which another employee is required to provide round-the-clock service.

Table 5. Comparison of financial parameters of pumping station upgrade options for Q1 2024.

	Unit\Variant	1	2	3	4	5	6
CE—Capital Expenditure	[MWh]	269,021	270,610	268,703	270,292	282,051	283,640
ACM—Additional annual Cost of Maintaining the pumping station	[MWh]	1030	1133	1030	1133	1030	1133
AEC—Additional annual Employee Cost	[MWh]	930	930	930	930	1239	1239
REC—annual Reduction in Energy Costs	[MWh]	−26,125	−24,978	17,986	19,095	22,354	23,374
PP—Payback Period	[years].	-	-	14.9	14.2	12.6	12.1
	Result:	Best		Second		Third	

The process of dewatering the goafs of liquidated mines is a costly process, and regardless of the level of modernization applied, it will remain a process that requires the support of a budget subsidy. In the study to determine some form of efficiency, it was assumed that a form of profit would be a reduction in budget subsidy. The annual reduction in energy costs (REC) was calculated by subtracting from the unpaid annual cost of purchasing electricity (CPE) and from the national grid the sum of the additional annual cost of maintaining the pumping station (ACM) and the additional annual employee cost (AEC) (Formula (1)) resulting from the necessary additional staffing. Other costs are not included in the calculations because they are incurred anyway regardless of the implementation of the pumping station upgrade.

$$REC = CPE - (ACM + AEC) \quad (1)$$

The terms in the above equation are as follows:

REC—annual Reduction in Energy Costs;

CPE—unpaid annual Cost of Purchasing Electricity;

ACM—additional Annual Cost of Maintaining the pumping station;

AEC—additional Annual Employee Cost.

Continuing this line of reasoning, the Payback Period (PP) of the additional expenditures for upgrading the pumping station was determined by dividing the expenditures (Capital Expenditure—CE) by the annual reduction in energy costs (REC) (Equation (2)).

$$PP = CE/REC \quad (2)$$

The terms in the above equation are as follows:

PP—Payback Period;

CE—Capital Expenditure;

REC—annual Reduction in Energy Costs.

According to Table 4, the most favorable variants in the criterion "Annual energy cost reduction" are Variant 6 and Variant 5. Both of these variants enable the retail sale of hydrogen. Large savings in the purchase of electricity are also provided by Variants 3 and 4, which provide for the wholesale sale of hydrogen. Unfortunately, for Variants 1 and 2, no reduction in energy purchase costs could be achieved.

A comparison of the payback time for the investment in modernization of the mine water pumping station aimed at protection against the "blackout" phenomenon for the evaluated variants, calculated in accordance with Equation (2), is presented in Table 5. According to the adopted methodology, the fastest payback time will be for Variants 6, 5, and 4, respectively. For the evaluated variants, it ranges from 12 to 15 years. Variants 1 and 2, which envisage burning all the hydrogen produced for captive use, will bring additional costs associated with the purchase of electricity after the upgrade. Due to the increasing costs of energy purchase, it was not possible to determine the payback time in Variants 1 and 2. From the point of view of economic criteria of economics, the implementation of these projects seems inefficient. If the only criterion for evaluating the presented variants were financial parameters, the most favorable variants in the reality of Q1 2024 would be Variants 6 and 5 (Table 5). The analysis of economic parameters conducted was carried out for the operation of the pumping station in its primary mode. Long-term operation in the emergency mode would worsen the efficiency of variants enabling the resale of a part of the hydrogen, making them functionally and economically similar to variants burning all the hydrogen produced.

Energy evaluation criteria were set for the primary mode of pumping station operation. When operating in the emergency mode, the greatest importance is given to satisfying the main sentence, i.e., blackout resistance, and the importance of energy criteria is no longer so important [9,10].

When evaluating designed energy solutions using RESs, the most frequently indicated parameter is the consumption of generated energy by RESs for its own purposes, i.e., energy self-consumption. In this study, the criterion "Self-consumption of energy" is understood as the direct use of "green" energy generated by the photovoltaic system plus the energy obtained from its own hydrogen to power the pumping station. When evaluating the criterion "Self-consumption of energy", the most favorable variants are Variants 1 and 2, which provide for the complete combustion of the generated hydrogen on-site for own purposes. These variants managed to cover up to 27% of their own energy needs. The rest, about 73% of the energy needs, must be financed from the financial security developed or from a budget subsidy [21,47]. In the other variants, which provide for the resale of a part of the generated hydrogen, the working photovoltaic farm covers only about 18% of the annual energy needs of the pumping station (Table 6).

Table 6. Comparison of energy and environmental parameters of pumping station upgrade options for Q1 2024.

	Unit\Variant	1	2	3	4	5	6
Autoconsumption of energy	[%]	26.75	26.99	18.26	18.57	18.26	18.57
Financial security for energy purchases	[%]	18.80	22.22	40.26	43.50	53.81	56.93
Covering the cost of energy purchases	[%]	45.55	49.21	58.53	62.08	72.07	75.51
Reducing the carbon footprint	[Mg CO_2/year]	7524	7591	5137	5224	5137	5224
	Result:	Best		Second		Third	

The criterion "Financial security of energy purchase" is understood as the share of electricity that can be purchased from the revenue from gas, heat, and treated water trading. In this criterion, Variants 6, 5, and 4 are the most favorable, respectively. These variants provide for the virtual storage of energy by its sale. The financial surplus generated on an annual basis would make it possible to cover between 40% and 57% of annual energy needs. Variants with all-hydrogen combustion develop a much smaller financial reserve (Table 6), allowing financing 18 to 22% of the annual energy requirements.

The same classification of variants was obtained in the criterion "Coverage of energy purchase costs", where "Self-consumption of electricity" and "Financial security of energy purchase" were added together. In this criterion, variants 6, 5, and 4 are consecutively the most favorable (Table 6). They allow to reduce the budget subsidy for the purchase of electricity at the pumping station by 62 to 76%.

Related to the criterion "Autoconsumption of electricity" is the criterion "Reduction of carbon footprint". The approximate reduction in the carbon footprint of the retrofitted pumping station was determined by multiplying the amount of energy replaced by the "green" energy generated by the photovoltaic farm (Formula (3)) when powering the pumping station (autoconsumption of "green" energy) by the electricity emission factor.

$$RCF = SC \times EEC \quad (3)$$

The terms in the above equation are as follows:

RCF—Reduction in Carbon Footprint;

SC—Self-Consumption of "green" energy;

EEC—Electricity Emission Factor.

According to the adopted procedure for calculating the criterion "Reduction of carbon footprint" (Formula (3)), Variants 1 and 2 are the most favorable (Table 6), allowing the reduction in equivalent CO_2 emissions to the atmosphere by about 7500 Mg CO_2 per year, when the other variants provide only about 5100 to 5200 Mg CO_2 per year [33,55].

Due to most energy criteria, the most favorable variants in the reality of Q1 2024 would be Variants 6 and 5 (Table 5). Variants 1 and 2 prove to be the best when assessing the degree of direct use for powering the pumping station of energy generated and stored at the pumping station site and when assessing the reduction in equivalent CO_2 emissions to the atmosphere.

The study analyzed selected safety variants against the "blackout" phenomenon, which can be applied to the analyzed mine water pumping station. Six feasible technical and organizational arrangements were presented for analysis. The variants are characterized by a similar level of initial outlays, but a different degree of security against the lack of electricity supply from the national grid and a different level of satisfaction of financing the purchase of electricity for the pumping station (Tables 1–6). All analyzed variants of modernization of pumping stations provide for generation of electricity only for own needs and do not require a license for generation and distribution of electricity. It should be assumed that their implementation in legal terms will not be difficult [3,4].

The variants that involve storing the generated surplus electricity in the form of hydrogen obtained by electrolysis and burning it entirely during periods of energy shortage (Variants 1 and 2) stand out for their great potential. These variants protect the pumping station to the greatest extent from external power shortages. Thanks to such a technical and organizational arrangement of the pumping station's operation, up to about 50% per year of independence of the pumping station from energy supplies from the national grid is achieved. The expenditures incurred on the modernization of the pumping station will, unfortunately, only increase the cost of purchasing electricity, and although Variants 1 and 2 should be considered the most secure in the event of a "blackout", their implementation in this form is economically inefficient. The decision to implement it can only be based on concern for the highest possible level of protection of the system against external power failure [24,44].

For economic reasons, the implementation of variants 3, 4, 5, and 6 was proposed as a modification of Variants 1 and 2. In all of them, the surplus electricity stored in the form of hydrogen is partially stored virtually by its wholesale (Variants 3 and 4) or retail sale at the company's own vehicle refueling station (Variants 5 and 6). For technical reasons of gas trading and to protect the pumping station from "blackout", it is envisaged to store in its own tanks a volume of hydrogen allowing five days' supply of pumping station equipment. A comparison of the functional parameters of the designed variants is presented in Figure 2. To allow comparison of parameters with different units and different absolute values, the current value of the analyzed parameter was divided by the largest value, reducing the parameters of the variants to unmandated values from 0 to 1. Particularly noteworthy in this group of variants are Variants 5 and 6. Despite the fact that the expenditures for their implementation are the highest, they are comparable in terms of Variants 1 and 2's pumping station operating time independent of energy supply from the national grid. In the basic mode of operation, the payback time for pumping station modernization in Variants 5 and 6 is the shortest, and the coverage of the cost of purchasing electricity from the national grid is provided to the greatest extent. The variation in the values of the functional parameters of Variants 5 and 6 is the smallest (Figure 2).

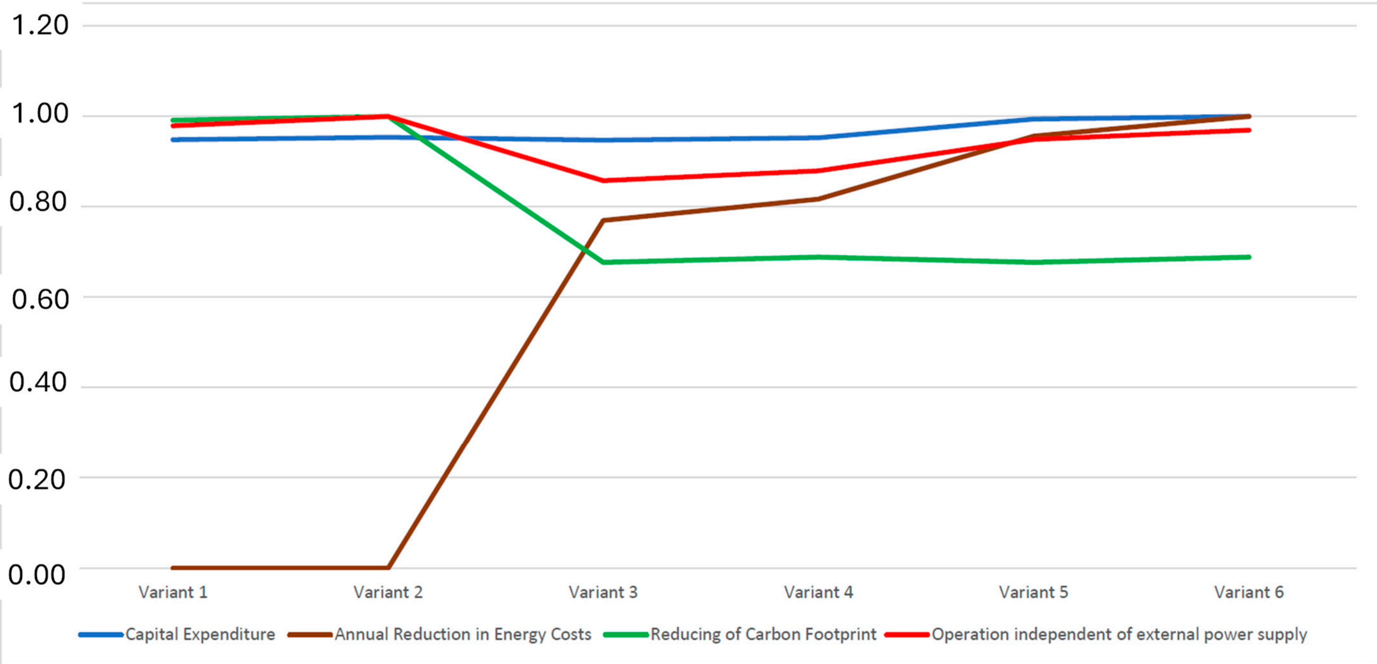

Figure 2. Comparison of functional parameters of the designed variants.

Increasing the volume of water treated, in spite of greater investment, increased the efficiency of the project. For image and social reasons [7,8], in the creation of new jobs, despite the increase in additional labor costs, Variants 5 and 6 are promoted (Table 5). Analyzing all the presented evaluation criteria, for the conditions of Q1 2024, the variant with partial retail sale of produced hydrogen and additional installation for obtaining rainwater from photovoltaic panels, that is, variant 6, is recommended for implementation. The low efficiency of the electrolysis process and the subsequent hydrogen combustion process of the entire volume of produced hydrogen makes the implementation of Variants 1 and 2 seem economically inefficient. The evaluation of alternatives was prepared in consideration of the circumstances that would be in effect during the first quarter of 2024. In the absence of any unforeseen and substantial alterations in circumstances in the near term, it is recommended that the analysis presented be adapted to the prevailing political, economic, and environmental circumstances. In the unpublished section of the study, due to the volume of the manuscript, it was determined that the economic parameters of the variants for the modernization of the pumping stations of the pit water are most influenced by the value of the currently negotiated electricity purchase price. An increase in the purchase price of electricity will result in enhanced profitability of the project. The decline in electricity prices observed recently, in the first and second quarters of 2024, has extended the Payback Period for the investment. The purchase of energy for the third and fourth quarters of 2024 has increased in the negotiated price of energy and a corresponding increase in the economic efficiency of the project. The largest component of the price of electricity is the cost of carbon dioxide emissions into the atmosphere. The increase in the price of electricity also has the paradoxical effect of improving the economic efficiency of the retrofit. The study also examined the influence of fluctuations in the EUR/PLN exchange rate, the cost of constructing a photovoltaic farm, and the price of hydrogen. To facilitate comparison of the impact of changes in these factors, their changes were analyzed with an assumed constant price of electricity negotiated in Q1 2024. The alterations in the parameters of the designed variants were frequently the consequence of an increase or decrease in the absolute value of the analyzed factors, with the magnitude of change often exceeding 15 percentage points. The analysis indicates that a change in the EUR/PLN exchange rate and a change in the purchase price of hydrogen result in a change in the parameters of the design variants with a very similar change in their values, expressed in percentage terms. The calculations do not indicate that the effect of changes in the absolute value of these factors is significant.

3.5. Additional Aspects of Ensuring General Security

In the functional layout of variants 3, 4, 5, and 6, it is questionable whether it makes sense to purchase stationary cogeneration engines, which, in the theoretical absence of a blackout, would never be put into operation [14,56]. However, for the sake of security of energy supply from the grid, it would be advisable to consider the purchase of mobile versions of these devices. In emergency situations, it would be possible to use them at other pumping stations as well, and the investment costs incurred could be divided among more locations. A mobile version of cogeneration engines could also counteract the effects of emergency situations by restoring power at facilities not owned by SRK S.A.

With a stationary version of combined heat and power (CHP) engines, all variants could serve the general security of the local community. In exceptionally acute emergencies of a particularly widespread "blackout" phenomenon, to the extent of its capabilities, the pumping station could supply, for example, parts of the city's critical infrastructure. Crisis-induced, emergency, and incidental abandonment of the so-called "island operation" would theoretically be possible at the request of the local government and with the approval of the local electricity supplier.

The existence of a pumping station in the proposed modernized version could counter another challenge to civilization. In a situation of energy shortage from the national grid, the operation of traditional water sources could be disrupted and there could be shortages in the supply of fresh water for food and technological purposes. A pumping station with a Mine Water Treatment Station (MWTS), operating independent of energy supplies, could at least partially secure these shortages. Mining regulations require that mining plants have pumping systems on board to drain the daily inflow of water in a period not exceeding 20 h. In addition, mine water pumping stations are also subject to this legislation. From this perspective, even a four-hour interruption in the power supply to the pumping station should not significantly affect the pumping process. In the case of the pumping station under review, continuous operation of all pumps for 18 h is sufficient to pump out the daily inflow of water. Moreover, all pumping stations have their own retention capacity. In the case of some of the pumping stations operating in a submerged system, even a few days' interruption in pumping will not significantly affect the overall safety of the system. Another aspect to consider is the necessity for ventilation of the pits of a deep-water pumping station. The same regulations require that mining plants resume operation of their main fans no longer than 10 min after the cessation of the previous operation. In the projects analyzed, this aspect could be resolved by utilizing 2.5 megawatt-hours (MWh) of battery energy storage. This would permit the independent powering of the critical equipment of the pumping station, obviating the necessity to operate in an "island" mode when powered by burned hydrogen. In addition, even in normal situations, the deteriorating quality and volume of water resources justifies the need to seek new opportunities to ensure the security of water supply. The company controls the operation of more than a dozen pumping stations, pumping out about 100 million m^3 of water annually (data for 2023) [13,20,28]. The task of the mine water pumping stations is to discharge into local watercourses, usually saline mine water [22,24,38]. The treatment of at least some mine water can partially satisfy social and industrial demands for freshwater use. With climate warming continuing, reducing the salt load discharged into local watercourses will also help reduce or perhaps prevent further algal blooms in Poland's major rivers [27,50].

4. Conclusions

Adverse climate change is increasing the threat of "backout" phenomena. "Blackout" as an unforeseen, prolonged lack of electricity supply from the national grid can cause threats to public safety. An extremely important challenge for SRK S.A. is to ensure the continuity of operation of the mine water pumping station system in the event of a sudden lack of power supply from the national grid. The pumping stations have a certain retention, and a short interruption in operation would not cause major consequences. A longer shutdown could lead to minor or major environmental problems. Such a situation would expose active mines and lower-lying areas to flooding. One of the worse case scenarios is the contamination of near-surface aquifers, sources of drinking water. Remediation of the resulting damage would require a large financial commitment and would likely drag on over time.

The proposed and evaluated pumping station modernization options functionally prepare the goaf dewatering process for emergency operation. The decision to adopt one of the proposed variants should be adjusted to the current economic, social, and political situation. For Q1 2024 conditions, the variant with partial retail sale of produced hydrogen and additional installation for rainwater harvesting from photovoltaic panels is recommended for implementation.

The presented options directed at achieving blackout resilience also solve, at least in part, other current problems of the company and local governments.

- Obtaining electricity from RESs will reduce the cost of purchasing electricity, which will reduce the need for budget support.
- Theoretically, once all approvals are in place, the pumping station could provide emergency power to the city's adjacent critical infrastructure.
- In the face of the so-called water crisis, the pumping station under study could become an alternative source of drinking water for the local community and secure the supply of drinking water even in the event of an extensive shortage of supply from the national grid.
- Reducing the salt load discharged into local watercourses will help reduce or prevent further algal blooms in Poland's major rivers.
- The draft decision options presented are aimed at maintaining existing jobs and creating new alternatives to mining.
- The proposed projects are in line with the European Union's work on sustainable development and the Just Transition process.
- The modernization described will promote the development of other sectors of the economy through the introduction of new technologies.
- The projects under discussion will create new markets related to modern transportation and "green energy".
- The projects are an opportunity to revitalize post-mining areas degraded by intensive mining.

Modernization of existing pumping stations combined with new technologies will be a form of partially self-financing solution of a closed-loop economy facility, positively perceived socially and in terms of image.

Author Contributions: Conceptualization, A.C., P.W., M.M., R.L., L.Z. and A.S.; methodology, A.C., P.W., M.M., R.L., L.Z. and A.S.; validation, A.C., P.W. and M.M.; formal analysis, A.C., P.W., M.M., R.L., L.Z. and A.S.; investigation, A.C.; resources, A.C.; data curation, A.C.; writing—original draft preparation, A.C.; writing—review and editing, A.C.; visualization, A.C.; supervision, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Andrzej Chmiela was employed by the Mines Restructuring Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Barszczowska, B. Hydrogen valleys as opportunities for SME in Poland. In *Preserving, Evaluating and Developing the Mediterranean*; Jurčević, K., Lipovčan, L.K., Medić, R., Ramljak, O., Eds.; Institute of Social Sciences Ivo Pilar, VERN University: Zagreb, Croatia, 2023; pp. 379–386. ISBN 978-953-8404-20-7.
2. Barszczowska, B. Polish Hydrogen Strategy. The role of hydrogen valleys. *Sci. J. Inst. Miner. Resour. Energy Manag. Pol. Acad. Sci.* **2023**, *1*, 109–116. [CrossRef]
3. Tokarski, S.; Magdziarczyk, M.; Smolinski, A. An Analysis of Risks and Challenges to the Polish Power Industry in the Year 2024. *Energies* **2024**, *17*, 1044. [CrossRef]
4. Tokarski, S.; Magdziarczyk, M.; Smolinski, A. Risk management scenarios for investment program delays in the Polish power industry. *Energies* **2021**, *14*, 5210. [CrossRef]
5. Gajdzik, B.; Wolniak, R.; Nagaj, R.; Grebski, W.W.; Romanyshyn, T. Barriers to Renewable Energy Source (RES) Installations as Determinants of Energy Consumption in EU Countries. *Energies* **2023**, *16*, 7364. [CrossRef]
6. Siostrzonek, T. The Mine Shaft Energy Storage System-Implementation Threats and Opportunities. *Energies* **2023**, *16*, 5615. [CrossRef]
7. Mhlongo, S.E. Evaluating the post-mining land uses of former mine sites for sustainable purposes in South Africa. *J. Sustain. Min.* **2023**, *22*, 3. [CrossRef]
8. Mhlongo, S.E.; Amponsah-Dacosta, F. A review of problems and solutions of abandoned mines in South Africa. *Int. J. Min. Reclam. Environ.* **2016**, *30*, 279–294. [CrossRef]
9. Krzemień, A.; Álvarez Fernández, J.J.; Riesgo Fernández, P.; Fidalgo Valverde, G.; Garcia-Cortes, S. Valuation of Ecosystem Services Based on EU Carbon Allowances-Optimal Recovery for a Coal Mining Area. *Int. J. Environ. Res. Public Health* **2023**, *20*, 381. [CrossRef]
10. Krzemień, A.; Álvarez Fernández, J.J.; Riesgo Fernández, P.; Fidalgo Valverde, G.; Garcia-Cortes, S. Restoring Coal Mining-Affected Areas: The Missing Ecosystem Services. *Int. J. Environ. Res. Public Health* **2022**, *19*, 14200. [CrossRef]
11. Chudy, K. Mine Water as Geothermal Resource in Nowa Ruda Region (SW Poland). *Water* **2022**, *14*, 136. [CrossRef]
12. Howaniec, N.; Zdeb, J.; Gogola, K.; Smolinski, A. Utilization of Carbon Dioxide and Fluidized Bed Fly Ash in Post-Industrial Land Remediation. *Materials* **2023**, *16*, 4572. [CrossRef]
13. Riesgo Fernández, P.; Rodríguez Granda, G.; Krzemień, A.; García Cortés, S.; Fidalgo Valverde, G. Subsidence versus natural landslides when dealing with property damage liabilities in underground coal mines. *Int. J. Rock Mech. Min. Sci.* **2020**, *126*, 104175. [CrossRef]
14. Villar, Y.; Menéndez, M.; Fernández, Z.; Bernardo, A. Sustainable earthworks: Optimization with the ICOM method. *Energy Rep.* **2020**, *6*, 404–419. [CrossRef]
15. Wojtacha-Rychter, K.; Król, M.; Gołaszewska, M.; Całus-Moszko, J.; Magdziarczyk, M.; Smoliński, A. Dust from chlorine bypass installation as cementitious materials replacement in concrete making. *J. Build. Eng.* **2022**, *51*, 104309. [CrossRef]
16. Peppas, A.; Kottaridis, S.; Politi, C. Potential Application of RES and Underground H_2 Storage in Abandoned Mines. *Mater. Proc.* **2023**, *15*, 30. [CrossRef]
17. Lyu, X.; Yang, K.; Fang, J.; Tang, J.; Wang, Y. Feasibility Study of Construction of Pumped Storage Power Station Using Abandoned Mines: A Case Study of the Shitai Mine. *Energies* **2023**, *16*, 314. [CrossRef]
18. Saik, P.; Falshtynskyi, V.; Lozynskyi, V.; Dychkovskyi, R.; Berdnyk, M.; Cabana, E. Substantiating the operating parameters for an underground gas generator as a basic segment of the mining energy-chemical complex. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1156*, 012021. [CrossRef]
19. Shavarskyi, I.; Falshtynskyi, V.; Dychkovskyi, R.; Akimov, O.; Sala, D.; Buketov, V. Management of the longwall face advance on the stress-strain state of rock mass. *Min. Miner. Depos.* **2022**, *16*, 78–85. [CrossRef]
20. Mercado, J.M.R.; Kawamura, A.; Amaguchi, H.; Rubio, C.J.P. Fuzzy based multi-criteria M&E of the integrated flood risk management performance using prio-rity ranking methodology: A case study in Metro Manila, Philippines. *Int. J. Disaster Risk Reduct.* **2021**, *64*, 102498. [CrossRef]
21. Rubio, C.J.P.; Yu, I.; Kim, H.; Kim, S.; Jeong, S. An investigation of the adequacy of urban evacuation centers using index-based flood risk assessment. *J. Korean Soc. Hazard Mitig.* **2019**, *19*, 197–207. [CrossRef]
22. Chmielewska, I.; Chalupnik, S.; Wysocka, M.; Smolinski, A. Radium measurements in bottled natural mineral-, spring- and medicinal waters from Poland. *Water Resour. Ind.* **2020**, *24*, 100133. [CrossRef]
23. Kaminski, P.; Niedbalski, Z.; Malkowski, P.; Bozic, D. Application of composite materials in underground mining industry-fore-shaft closing platform. *Min. Mach.* **2022**, *40*, 1–13. [CrossRef]
24. Bondaruk, J.; Janson, E.; Wysocka, M.; Chałupnik, S. Identification of hazards for water environment in the Upper Silesian Coal Basin caused by the discharge of salt mine water containing particularly harmful substances and radionuclides. *J. Sustain. Min.* **2015**, *14*, 179–187. [CrossRef]
25. Mitchell, A.; Mackasey, W.O. A systematic inventory of abandoned mines—A powerful tool for risk management. *Int. J. Surf. Min. Reclam. Environ.* **1997**, *11*, 83–90. [CrossRef]
26. Kuzmenko, O.; Dychkovskyi, R.; Petlovanyi, M.; Buketov, V.; Howaniec, N.; Smolinski, A. Mechanism of Interaction of Backfill Mixtures with Natural Rock Fractures within the Zone of Their Intense Manifestation while Developing Steep Ore Deposits. *Sustainability* **2023**, *15*, 4889. [CrossRef]

27. Wysocka, M.; Chalupnik, S.; Chmielewska, I.; Janson, E.; Radziejowski, W.; Samolej, K. Natural Radioactivity in Polish Coal Mines: An Attempt to Assess the Trend of Radium Release into the Environment. *Int. J. Mine Water* **2019**, *38*, 581–589. [CrossRef]
28. Smith, F.W.; Underwood, B. Mine closure: The environmental challeng. *Min. Technol.* **2000**, *109*, 202–209. [CrossRef]
29. Wrona, P. The influence of climate change on CO2 and CH4 concentration near closed shaft—Numerical simulations. *Arch. Min. Sci.* **2017**, *62*, 639–652. [CrossRef]
30. Gawęda, A. ESG Rating and Market Valuation of the Firm: A Sector Approach. *Eur. J. Sustain. Dev.* **2022**, *11*, 91. [CrossRef]
31. Raza, A.; Gholami, R.; Rezaee, R.; Rasouli, V.; Rabiei, M. Significant aspects of carbon capture and storage—A review. *Petroleum* **2019**, *5*, 335–340. [CrossRef]
32. Salom, A.T.; Kivinen, S. Closed and abandoned mines in Namibia: A critical review of environmental impacts and constraints to rehabilitation. *S. Afr. Geogr. J.* **2020**, *102*, 389–405. [CrossRef]
33. Seheda, M.S.; Beshta, O.S.; Gogolyuk, P.F.; Blyznak, Y.V.; Dychkovskyi, R.D.; Smolinski, A. Mathematical model for the management of the wave processes in three-winding transformers with consideration of the main magnetic flux in mining industry. *J. Sustain. Min.* **2024**, *23*, 20–39. [CrossRef]
34. Doorga, J.R.S.; Hall, J.W.; Eyre, N. Geospatial multi-criteria analysis for identifying optimal wind and solar sites in Africa: Towards effective power sector decarbonization. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112107. [CrossRef]
35. Khomenko, D.; Jelonek, I. Study of a Low-Cost Method for Estimating Energy Fuel Resources in Anthropogenic Sediments. *Manag. Syst. Prod. Eng.* **2023**, *31*, 434–441. [CrossRef]
36. Kalantari, H.; Ghoreishi-Madiseh, S.A. Hybrid Renewable Hydrogen Energy Solution for Remote Cold-Climate Open-Pit Mines. *Hydrogen* **2022**, *3*, 312–332. [CrossRef]
37. Bartela, Ł.; Ochmann, J.; Waniczek, S.; Lutyński, M.; Smolnik, G.; Rulik, S. Evaluation of the energy potential of an adiabatic compressed air energy storage system based on a novel thermal energy storage system in a post mining shaft. *J. Energy Storage* **2022**, *54*, 105282. [CrossRef]
38. Labus, K.; Tarkowski, R.; Wdowin, M. Modeling gas-rock-water interactions in carbon dioxide storage capacity assessment: A case study of Jurassic sandstones in Poland. *Int. J. Environ. Sci. Technol.* **2015**, *12*, 2493–2502. [CrossRef]
39. Takach, M.; Sarajlić, M.; Peters, D.; Kroener, M.; Schuldt, F.; von Maydell, K. Review of Hydrogen Production Techniques from Water Using Renewable Energy Sources and Its Storage in Salt Caverns. *Energies* **2022**, *15*, 1415. [CrossRef]
40. Smolinski, A.; Howaniec, N. Hydrogen energy, electrolyzers and fuel cells—The future of modern energy sector. *Int. J. Hydrogen Energy* **2020**, *45*, 5607. [CrossRef]
41. Vladyko, O.; Maltsev, D.; Sala, D.; Cichoń, D.; Buketov, V.; Dychkovskyi, R. Simulation of leaching processes of polymetallic ores using the similarity theorem. *Rud.-Geološko-Naft. Zb.* **2022**, *37*, 169–180. [CrossRef]
42. Fidalgo-Valverde, G.; Menéndez-Díaz, A.; Krzemień, A.; Riesgo-Fernández, P.; Marqués Sierra, A.L. Environmental risk assessment in coal mining with methane degassing. In Proceedings of the 11th International Symposium on Occupational Health and Safety (SESAM), Bucharest, Romania, 18 October 2023. [CrossRef]
43. Kononenko, M.; Khomenko, O.; Kovalenko, I.; Kosenko, A.; Zahorodnii, R.; Dychkovskyi, R. Determining the performance of explosives for blasting management. *Rud.-Geološko-Naft. Zb.* **2023**, *38*, 19–28. [CrossRef]
44. Bazaluk, O.; Sadovenko, I.; Zahrytsenko, A.; Saik, P.; Lozynskyi, V.; Dychkovskyi, R. Forecasting Underground Water Dynamics within the Technogenic Environment of a Mine Field. *Case Study Sustain.* **2021**, *13*, 7161. [CrossRef]
45. Biały, W.; Grebski, W.; Galecki, G.; Kaniak, W. Environmental Impact of The Mechanical Coal Processing Plant. *Acta Montan. Slovaca* **2020**, *25*, 139. [CrossRef]
46. Mallikarjun Rao, P.; Pathak, K. Socio-economic impacts of mine closure: A case study using satellite imagery. *Int. J. Environ. Stud.* **2005**, *62*, 555–570. [CrossRef]
47. Mucha, Z.; Generowicz, A.; Wojcik, W.; Jóźwiakowski, K.; Baran, S. Application of multi-criterial analysis to evaluate the method of utilization of sludge from small wastewater treatment plants with sustainable development of rural areas. *Environ. Prot. Eng.* **2016**, *42*, 97–105. [CrossRef]
48. Gawęda, A. Sustainability Reporting: Case of European Stock Companies. *Eur. J. Sustain. Dev.* **2021**, *10*, 41–53. [CrossRef]
49. Fernández-Muñiz, Z.; Pallero, J.L.G.; Fernández-Martínez, J.L. Anomaly shape inversion via model reduction and PSO. *Comput. Geosci.* **2020**, *140*, 104492. [CrossRef]
50. Łabaj, P.; Wysocka, M.; Janson, E.; Deska, M. Application of the Unified Stream Assessment Method to Determine the Direction of Revitalization of Heavily Transformed Urban Rivers. *Water Resour.* **2020**, *47*, 521–529. [CrossRef]
51. Kaczmarek, J.; Kolegowicz, K.; Szymla, W. Restructuring of the Coal Mining Industry and the Challenges of Energy Transition in Poland (1990–2020). *Energies* **2022**, *15*, 3518. [CrossRef]
52. Krzemień, A.; Frejowski, A.; Fidalgo Valverde, G.; Riesgo Fernández, P.; Garcia-Cortes, S. Repurposing End-of-Life Coal Mines with Business Models Based on Renewable Energy and Circular Economy Technologies. *Energies* **2023**, *16*, 7617. [CrossRef]
53. Gawęda, A.; Sajnóg, A. Cross-sectoral detection of the Return on Equity determinants based on the 7-factor DuPont model. *Leg. Econ. Stud. Econ. Law* **2020**, *114*, 217–234. [CrossRef]
54. Gawęda, A.; Złoty, M. The impact of ESG ratings on the market performance of commodity stock sector before and during the COVID-19 pandemic. *Econ. Law Econ. Law* **2023**, *22*, 531–553. [CrossRef]
55. Prakash Pandey, B.; Prasad Mishra, D. Improved Methodology for Monitoring the Impact of Mining Activities on Socio-Economic Conditions of Local Communities. *J. Sustain. Min.* **2022**, *21*, 65–79. [CrossRef]

56. Kaczmarek, J. The Balance of Outlays and Effects of Restructuring Hard Coal Mining Companies in Terms of Energy Policy of Poland PEP 2040. *Energies* **2022**, *15*, 1853. [CrossRef]
57. Woszczynski, M.; Jasiulek, D.; Jagoda, J.; Kaczmarczyk, K.; Matusiak, P.; Kowol, D.; Marciniak, B. Monitoring of the mining waste neutralization facility of LW Bogdanka. *Acta Montan. Slovaca* **2023**, *28*, 236–249. [CrossRef]