energies

MDPI

Article

The Cost Reduction Analysis of Green Hydrogen Production from Coal Mine Underground Water for Circular Economy

Małgorzata Magdziarczyk [1], Andrzej Chmiela [2], Roman Dychkovskyi [3] and Adam Smoliński [4,*]

[1] Faculty of Economics and Management, Opole University of Technology, 45-758 Opole, Poland; m.magdziarczyk@po.edu.pl
[2] Mines Restructuring Company (Spółka Restrukturyzacji Kopalń S.A.), 41-914 Bytom, Poland; achmiela@srk.com.pl
[3] Faculty of Management, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Krakow, Poland; dychkovskyi@agh.edu.pl
[4] Central Mining Institute, Plac Gwarkow1, 40-166 Katowice, Poland
* Correspondence: smolin@gig.katowice.pl

Abstract: The novelty of the paper is the analysis of the possibilities of reducing the operating costs of a mine water pumping station in an abandoned coal mine. To meet the energy needs of the pumping station and reduce the carbon footprint, "green" energy from a photovoltaic farm was used. Surplus green energy generated during peak production is stored in the form of green hydrogen from the water electrolysis process. Rainwater and process water are still underutilized sources for increasing water resources and reducing water stress in the European Union. The article presents the possibilities of using these waters, after purification, in the production of green hydrogen by electrolysis. The article also presents three variants that ensure the energy self-sufficiency of the proposed concepts of operation of the pumping station.

Keywords: renewable sources of energy; energy storage; revitalization of post-mining areas; mine liquidation

check for updates

Citation: Magdziarczyk, M.; Chmiela, A.; Dychkovskyi, R.; Smoliński, A. The Cost Reduction Analysis of Green Hydrogen Production from Coal Mine Underground Water for Circular Economy. *Energies* **2024**, *17*, 2289. https://doi.org/10.3390/en17102289

Academic Editor: David Borge-Diez

Received: 2 April 2024
Revised: 27 April 2024
Accepted: 6 May 2024
Published: 9 May 2024

1. Introduction

Climate change and the constant increase in temperature are forcing us to take action to reduce the greenhouse effect. One of the main emitters of greenhouse gases is the energy industry, which is still mainly based on generating energy from fossil fuels.

Current efforts are aimed at resigning from fossil fuels and moving toward low- and zero-emission energy sources. The main emphasis is on promoting the use of wind and solar energy. The disadvantage of these solutions is their lack of stability and overproduction of energy on sunny and windy days. These unstable energy sources require the use of effective systems for storing this surplus energy, which can be used on days when there will be no production from renewable energy sources (cloudy/no windy days) [1,2]. One of the options for energy storage is to store it in the form of hydrogen, produced by electrolysis [3]. The article presents the idea of using rainwater and process water, after appropriate purification, as a water source for the electrolysis process. This form of hydrogen production is the most advantageous from the point of view of zero-emission energy and transport [4–6].

Currently, over 95% of hydrogen is obtained from fossil fuels, which is accompanied by greenhouse gas emissions. An alternative option is to obtain hydrogen in an emission-free way, i.e., in the process of water electrolysis. It is necessary to use energy from renewable energy sources in the electrolysis process so as to obtain green hydrogen.

Water electrolysis in the European Union is perceived as an effective source of "green" hydrogen and one of the main conditions for achieving climate neutrality in Europe by 2050, which is a key assumption of the so-called Green Deal. The global shortage of drinking water forced us to search for new sources of water supply for technological purposes. Rainwater is an underestimated method of obtaining water in Europe. In order to optimize water circulation and ensure independence from the power supply from the water supply network, it is necessary to take action to reduce the consumption of energy and water from traditional sources.

Technological progress, the rapid decrease in prices of energy from renewable sources, and the need to drastically reduce greenhouse gas emissions clearly indicate the possibility of using hydrogen as a clean energy carrier [7,8]. Hydrogen can be produced from both renewable and non-renewable sources. Global hydrogen production in 2020 will rely almost entirely on fossil fuels [9,10]. Commercial hydrogen production is currently based primarily on steam reforming of natural gas and partial oxidation of coal. Clean hydrogen production involves the use of biomass and solar hydrogen production methods. The anticipated transition to a hydrogen energy system is likely to be based on H_2 produced by natural gas reforming or electrolysis [11,12]. One possible reason for the development of low-carbon hydrogen may be the high cost of production. The average cost of producing hydrogen from electrolysis of water using energy from renewable sources is currently about 6–16 times higher than for hydrogen from natural gas.

Hydrogen production through electrolysis requires relatively large amounts of electricity and water. To produce 1 kg of hydrogen, approximately 50–55 kWh of energy and 9 kg of water are needed. Technical considerations and potential water losses for maintaining the efficiency of the equipment, in extreme cases, cause water consumption by the electrolyzer to increase up to approximately 22 $dm^3/kg\ H_2$ [10,12]. The deteriorating quality and volume of water resources justify the need to look for new possibilities to ensure the safe operation of water supply systems. Due to lower supply risk and lower costs, the public water supply is the most suitable source of water for electrolysis [13,14]. The shortage of clean water in the world means that the use of tap water for hydrogen production may be limited. Therefore, it is necessary to find alternative, stable sources of water to power the electrolysis process. The use of purified rainwater and process water for this purpose, presented in this work, can ensure the proper functioning of the water electrolysis process. The global problem with access to clean water has led to the consideration of unconventional ways of obtaining it. To reduce the risk of drinking water shortages, efforts should be made to increase water recycling. Each case of using water extraction processes to power electrolyzers must be considered individually. The selection of the appropriate method depends on the amount, availability, mineralization of water, and climatic conditions. The decision to choose the specific water treatment technology must be preceded by appropriate analyses [15–17]. To produce very pure hydrogen (purity above 99.999% hydrogen 5.0), deionized water is needed [18,19], with a conductivity of no more than 5 μS/cm [20,21], free from any dissolved substances and impurities. Impurities in the water may negatively affect the electrolysis process and the life of the electrodes in the electrolyzer. This mainly concerns the deposition of contaminants on the surface of the electrodes and/or in the membranes. In order to prepare rainwater and process water, it is recommended to use the process line consisting of several water treatment processes. Membrane techniques allow for the recovery of water from rainwater and process water, which, after treatment, will meet the requirements for water intended for human drinking or powering electrolyzers for hydrogen production.

The planned project of energy self-sufficiency of mine water pumping stations may have a significant impact on the social and economic structure of each mining region [17,22]. The project is part of the Just Transition process and is an opportunity for regional development thanks to the introduction of modern technological solutions [23,24]. The variant project in question will create new markets related to modern transport and an energy mix based partly on renewable energy [19,25]. The presented variants of energy self-sufficiency also provide the opportunity to revitalize post-mining assets, which would otherwise be difficult to adapt to another purpose [26–28].

One of the tasks of Spółka Restrukturyzacji Kopalń S.A. (SRK S.A.) is the continuous drainage of goafs from liquidated mines [17,29]. Another socially important task is the management of assets left by liquidated hard coal mines [30–32]. Cessation of drainage, apart from flooding active mines and low-lying areas on the surface, could lead to contamination of drinking water intakes [22,33]. The company pumps out approximately 100 million m^3 of water annually using deep-well or stationary drainage methods (data for 2023). The purchase of electricity is one of the largest components of the costs necessary to conduct this part of SRK S.A.'s activities [14,34]. Consumption of "black" energy in the company in 2023 amounted to approximately 300 GWh, which corresponds to approximately 160 million Mg of CO_2 equivalent emissions into the atmosphere [35,36]. In order to reduce the carbon footprint of SRK S.A.'s operations, it is necessary, among other things, to reduce the need to purchase electricity. This can be achieved by modernizing the technical equipment used or by purchasing energy from renewable sources. Financial analysis shows that a faster, cheaper, and more effective method is the use of renewable energy sources combined with the storage of temporary surpluses of generated electricity. The second environmental option for abandoned mines is to treat at least some of the pumped mine water. The amount of water treated depends on the economics of the treatment process. Under current market conditions, only a portion of the pumped water can be effectively treated.

The management of mine and rainwater combined with the development of the concept for the pilot solution for energy self-sufficiency in an exemplary mine water pumping station was the main research goal. Additionally, a very important design element was to reduce the negative impact of polluted water emissions on the environment and increase the financial efficiency of the project [37,38]. The process of pumping water from abandoned mines is inherently expensive. Simply pumping the water is more expensive than purchasing tap water. In addition, mine waters are mineralized waters that require treatment. The degree of mineralization increases with depth. It is possible to selectively pump water with different degrees of mineralization. According to the Ukrainian experience, it would be possible to treat a part of the pumped water [7,39]. Excluding the cost of pumping, the cost of treating less mineralized waters from shallower depths will not exceed the purchase price of pure piped water. Treatment of more mineralized water coming from greater depths is technically possible, but the cost of treatment would already exceed the purchase price of pure tap water. For this reason, the work limits water treatment to less mineralized water. In addition to ecological goals and covering the pumping station's energy needs with "green" energy, the project aims to revitalize the pumping station facilities, maintain the existing ones, and possibly create new jobs that are alternative to mining.

2. Materials and Methods

A stationary drainage system is maintained in the analyzed pumping station, which is based on the network of approximately 8 km of underground workings adapted for the pumping station and two shafts left for ventilation of these workings. In accordance with the water law permit, water accumulating underground is pumped through pipelines to the surface, where it flows by gravity through the collector to the nearby river [39,40]. To protect rivers and watercourses, constant monitoring of discharged water and pollutants dissolved in it by specialized services of SRK S.A. is necessary [1,15]. The ideal situation would be to completely eliminate these emissions from the environment [37,38,41]. So as to support the operation of the pumping station, 11 post-mining facilities are left, and the unnecessary ones are liquidated. The remaining surface structures are accompanied by the reclaimed area of the former railway siding and storage yards. The reclaimed area near the pumping station has a southern exposure and a regular shape, allowing for the orderly development of panels. It also has suitable access for technical vehicles, as well as closely located power points for medium- and high-voltage installations. About 90 people work in the pumping station, and most of them are underground workers. In 2023, the company pumped out approximately 1 million m3 of mine water. At the pumping station, due to the capacity of the pumps, dewatering is performed for approximately 6 h per day, every day of the year. To facilitate calculations in the pump station model used, it is assumed that the operation of other pump station equipment during the rest of the day is equivalent to an additional hour of pumping. The ventilation system is based on 2 × 92 kW main fans. The operation of the fans is continuous. The pumping station requires approximately 6 GWh of electricity to perform its activities. The mine water pumping station is located in one of the districts of a large city in the Silesian agglomeration.

One of the ways to reduce the demand for purchasing electricity from the grid is to use renewable sources of energy [35,42]. Because of the low windiness of the Upper Silesia region and the neighborhood of residential buildings, the use of wind energy is abandoned in the project. Due to the protection of the local energy market and the limited absorption capacity of the local energy network, the condition for the implementation of the project is not to transfer excess generated energy to the national grid. The project involves the construction of a photovoltaic farm next to the mine water pumping station with a generating capacity of approximately 7.5 MWp. Such a farm can produce approximately 8.8 GWh of "green", "clean" electricity annually, but the relatively low efficiency of the electrolysis process and subsequent combustion of hydrogen in cogeneration engines will allow the recovery of the assumed 6 GWh of electricity necessary for the pumping station from the stored hydrogen. Insolation on sunny days meets the energy needs of the pumping station [43]. The proper functioning of most renewable energy installations is not possible without energy storage technology during periods of increased energy production [14,24]. Storing energy in green hydrogen produced through electrolysis allows for very effective long-term storage of generated energy surpluses and their use during times of greater demand for electricity. Hydrogen can be produced using various processes and energy sources. Green hydrogen is produced using renewable energy and is one of the key elements of the sustainable energy transformation concept. The energy self-sufficiency project of the mine water pumping station assumes storing excess energy in hydrogen obtained from water electrolysis [5,44]. Energy storage through battery systems or shaft installations allows for short-term storage. For financial reasons, storing energy in the form of hydrogen is more attractive than storing it in battery systems, for example. According to a market study (Q4 2023), storing 1 MWh in the form of hydrogen is 3.5 times cheaper than in battery systems. The project only predicts the construction of the small battery energy storage facility to provide power at night and buffer the generated energy or the possible need to stabilize the operation of the electrolyzer.

3. Results and Discussion

Three variants of the operation of an energy-self-sufficient mine water pumping station were adopted for the analysis, differing in the scope of modernization. In all variants, the modernization of the pumping station includes the following constructions:

- Photovoltaic farms with a capacity of approximately 7.5 MWp;
- Electrolyzer;
- Battery energy storage with a capacity of 1 MWh;
- Thermal energy storage;
- Hydrogen storage tank;
- Oxygen storage tank;
- Cogeneration engines or hydrogen cells required to power pumping station equipment during periods of non-sunny conditions or at night.

In the second variant, it was additionally proposed to build the Mine Water Treatment Station, and in the third variant, an additional installation for collecting rainwater and process water. The project assumed the use of all green energy produced for its own needs without the need to transfer the surplus electricity produced to the local distributor's network. It was assumed that excess electricity produced by the photovoltaic farm would be stored in the form of green hydrogen obtained through electrolysis. The hydrogen produced will be stored and used on-site to produce electricity during periods of shortage. Any excess of hydrogen will be transported to another pumping station to generate electricity there. The sale of produced oxygen will cover part of the costs of purchasing "black" energy.

The calculations assumed that it would be necessary to use 9 kg of water to produce 1 kg of hydrogen [43,45]. It was also assumed that the income from the sale of treated water and produced oxygen would be directed to the purchase of electricity from the local supplier. It was assumed that these media would be sold to local distributors for 60% of their retail price.

The amount of energy that could be used by the pumping station was calculated as the own consumption of the part of the electricity produced by the photovoltaic installation and energy recovered from the stored hydrogen, plus electricity purchased from the local supplier from the income of the oxygen's sale and treated drinking water. Covering the energy demand of the pumping station (expressed in %) for the considered variants is presented in Tables 1–5 and is the ratio of the amount of energy that can be used by the pumping station to the actual demand of the pumping station. Covering the company's energy demand is given as the ratio of the amount of energy that can be used by the pumping station to the company's demand, and it is expressed as a percentage.

3.1. Variant I Referring to the Modernization of the Pumping Station by Building a Photovoltaic Farm and Storing Surplus Energy in the Form of "Green Hydrogen"

In the basic version of modernization, on sunny days, the photovoltaic farm produces electricity that powers the pumping station equipment. When energy production exceeds the demand of the pumping station, the excess energy is directed to power the electrolyzer. Any temporary excesses of generated electricity as "waste" energy will be directed to a buffer battery energy storage facility. After charging the warehouse, the electrolysis process will begin, and it will continue until the warehouse is unloaded. In the first basic variant, due to the contamination of mine water, it was assumed that the electrolyzer would be powered by purchased drinking water from the municipal water supply system [46,47]. Mine water will only be used to cool the electrolysis process itself. Thermal energy from cooling the electrolyzer will be stored in the underground heat storage and used for its own needs in the pumping station, for example, to heat utility water in the mining bath. When the electricity production from the photovoltaic installation is low, the produced energy will be collected in the buffer battery energy storage for a short-term full power supply of the electrolyzer after the storage is full [35,36].

Produced oxygen and hydrogen will fulfill storage tanks via compressors. Stored oxygen will be sold to wholesalers specializing in gas trading. Taking into account the obtained income, the "black energy" from the local supplier could be covered. In this system, the auto-consumption will amount to approximately 42% of produced green energy. The rest will go directly to the electrolysis process. During periods of demand for electricity, hydrogen will fulfill cogeneration engines or hydrogen cells, producing electricity and heat. The generated electricity will power the pumping station equipment. The produced thermal energy will be directed to the underground heat storage facility. For energy prices in the fourth quarter of 2023, the proposed investment would fully meet the energy needs of the pumping station. This corresponds to the reduction of approximately 5175 Mg of CO_2 equivalent emissions into the atmosphere. The considered variant enables the creation of up to 8 jobs.

Table 1 presents the estimated financial results of the discussed project variant for the negotiated purchase price of electricity in the fourth quarter of 2023. To calculate the payback period, the full investment cost of modernizing the pumping station and any additional costs resulting from the modernization were assumed. These additional costs are the full cost of operating the pump station after modernization minus the cost of operating the pump station before modernization. In the calculation, the benefit is the amount of unpaid electricity bills after the modernization. The amount of expenditure on modernization and the estimated reduction in the costs of purchasing electricity in

Table 1 and in all tables are given as a multiple of the expenditure necessary to finance the construction of basic variant I of the modernization of the pumping station.

Table 1. Forecasted parameters of the pumping station project with the storage of surplus energy in the form of "green hydrogen"—basic variant I.

A	B	C
Estimated reduction in the electricity purchase costs	0.076	[multiple of expenditure on the basic variant]
Total expenditure	1.00	
Expenditure return period	13.1	[years]
Energy needs cover of the pumping station	100.6	[%]
Energy needs cover of the company	2.2	[%]
Equivalent reduction in CO_2 emissions	5175	[Mg CO_2/year]
Auto-consumption of generated electricity	42.8	[%]
Maintenance of workplaces	8	[items]

3.2. Variant II Referring to the Modernization of the Pumping Station by Building a Photovoltaic Farm and Storing Surplus Energy in the Form of "Green Hydrogen" along with the Construction of the Mine Water Treatment Station (MWTS)

Due to the search for alternative possibilities of obtaining and stabilizing water supplies for the electrolysis process, the possibility of building the Mine Water Treatment Plant (MWTS) adapted to the volume of water pumped by the pumping station was adopted as the optional solution [20,23]. The pumping station provides a constant stream of 1.9 m^3/h of moderately saline water to the Mine Water Treatment Station, 24 h a day. Using the full volume of pumped mine water, the pumping station would provide the electrolyzer's demand for clean, treated water and could supply the local water network with water treated for human consumption as an alternative source of drinking water (World Health Organization recommendations). In the field of mine water treatment, SRK S.A. signed letters of intent with several local governments regarding the possible future receipt of treated mine water. The estimated costs of the construction of the MWTS and water treatment were based on pilot studies already carried out by the company in the pumping stations with comparable mine water parameters.

The installation of the MWTS with a capacity of 1.1 million m^3 will increase the annual energy demand of the pumping station by approximately 1.75 GWh. Part of the treated water will be directed to the electrolyzer, which will make the pumping station independent of drinking water supplies from the local water supply system. The income from the sale of the remaining part of the treated water will be the additional source of financing for the purchase of the missing part of the electricity from the local supplier. Table 2 presents the estimated basic efficiency indicators of the option of modernizing the pumping station with the construction of the MWTS.

Increasing expenditures by 37 percentage points increased annual savings when purchasing electricity by 22 percentage points. Expenditure on the construction of the Mine Water Treatment Station extended the expenditure return period by 1 year compared to the basic version (variant I). The option of building the MWTS near the pumping station area slightly reduced the coverage of the pumping station's energy demand, which, for energy purchase prices from the fourth quarter of 2023, slightly exceeds the pumping station's needs. However, it should be remembered that in variant II with the MWTS, the energy demand increased by approximately 21 percentage points compared to basic variant I. It was estimated that the auto-consumption of generated "green" electricity would be approximately 45.6%. This corresponds to the reduction of 6604 Mg of CO_2 equivalent emissions into the atmosphere. This variant of modernization of the pumping station created approximately 14 alternative jobs to mining.

Table 2. Forecasted parameters of the pumping station project with the construction of the Mine Water Treatment Station (MWTS)—variant II (MWTS).

A	B	C
Estimated reduction in the electricity purchase costs	0.098	[multiple of expenditure on the basic variant]
Total expenditure	1.37	
Expenditure return period	14.1	[years]
Energy needs cover of the pumping station	100.3	[%]
Energy needs cover of the company	2.8	[%]
Equivalent reduction in CO_2 emissions	6604	[Mg CO_2/year]
Auto-consumption of generated electricity	45.6	[%]
Maintenance of workplaces	14	[items]

3.3. Variant III Referring to the Modernization of the Pumping Station by Building a Photovoltaic Farm and Storing Surplus Energy in the Form of "Green Hydrogen" along with the Construction of the Mine Water Treatment Station (MWTS) and an Installation for Collecting Rainwater and Process Water

An optional extension for variant II with the construction of the Mine Water Treatment Station (MWTS) is the addition of installations for collecting rainwater and process water and adapting the capabilities of the MWTS to the increased volume of water requiring treatment in variant III [5,48]. This solution provides for additional treatment of rainwater and process water from washing photovoltaic panels jointly obtained from the rainwater collection system. Due to the annual rainfall, the surface of the roofs, and the surface of the photovoltaic panels, it was estimated that it would be possible to collect about half of the rainwater falling on these surfaces, i.e., about 0.4 million m^3 of water. It was also estimated that it would be possible to obtain about half of the water directed to washing the panels, which gives another approximately 0.1 million m^3. Due to the relatively low contamination of water from the mining baths, the project included an additional volume of approximately 0.1 million m^3 of water that could be treated. In this variant, it is necessary to slightly increase the water treatment capacity of the MWTS to approximately 1.2 million m^3 of water per year. The additional management of mixed mine water, rainwater, and process water further reduces water shortages and the discharge of polluted mine water into watercourses. It also reduces the emission of salts and other pollutants into the environment. The expansion of the MWTS will increase the annual energy demand of the pumping station by an additional approximately 0.1 GWh (26 percentage points compared to basic variant I and 6 percentage points compared to variant II with the MWTS). The necessary part of the treated water will be directed to power the electrolyzer, and the income from the sale of the remaining part of the treated water will be used to purchase the missing part of the electricity. Table 3 presents the basic efficiency indicators for the modernization option of the pumping station with the construction of the MWTS and the installation of rainwater and process water collection.

Increasing expenditure by 39 percentage points compared to basic variant I increased the estimated annual reduction in the costs of purchasing electricity by 27 percentage points. Expenditure on the expansion of the Mine Water Treatment Station and the construction of the rainwater collection installation extended the expenditure return period by approximately 10 months compared to the version with MWTS (variant II). The option of building the MWTS and building the rainwater and process water collection installation at the pumping station for energy purchase prices from the fourth quarter of 2023 increased the estimated reduction in electricity purchase costs. For these conditions, the pumping station will have an overproduction of electricity, which will exceed the pumping station's demand by approximately 6 percentage points. The surplus obtained can be used in another pumping station after transporting and burning the stored hydrogen there. It was estimated that the auto-consumption of the generated "green energy" would be approximately 46%. This corresponds to the equivalent emission of 7027 Mg of CO_2 into the atmosphere. For proper functioning in this modernization variant, it is planned to create up to 17 new alternative-to-mining jobs for employees relocated from other branches of the company.

Table 3. Forecasted parameters of the pumping station project with the construction of the Mine Water Treatment Station (MWTS) and the installation for collecting rainwater and process water—variant III.

A	B	C
Estimated reduction in the electricity purchase costs	0.104	[multiple of expenditure on the basic variant]
Total expenditure	1.39	
Expenditure return period	13.3	[years]
Energy needs cover of the pumping station	106.7	[%]
Energy needs cover of the company	2.95	[%]
Equivalent reduction in CO_2 emissions	7027	[Mg CO_2/year]
Auto-consumption of generated electricity	46.3	[%]
Maintenance of workplaces	17	[items]

About 95% of the hydrogen produced today comes from fossil fuels. Its production is accompanied by greenhouse gas emissions. The alternative proposal is to receive the so-called green hydrogen through water electrolysis using electricity from renewable energy sources (wind or photovoltaic farms). Green hydrogen is indicated in every hydrogen strategy of all EU countries as a guarantee of achieving climate neutrality in the European Union by 2050. The bottleneck may be the lack of access to a sufficient amount of water that can be used to produce green hydrogen. The idea of using rainwater and process water as the water source for the electrolysis process seems to be the partial solution to this problem.

Hydrogen production using renewable energy sources is recognized as one of the elements of Europe's green transformation. The development of the hydrogen economy, in accordance with the European and Polish Hydrogen Strategy, takes into account, for instance, the use of electrolyzers for hydrogen production.

As a result of the research, three variants of the concept of the pilot solution for energy self-sufficiency, as shown in the example of the mine water pumping station, were proposed. All variants assume the conversion of energy surpluses produced by the photovoltaic farm built in the pumping station into hydrogen. The variants are designed to use the produced hydrogen exclusively for their own needs. The produced hydrogen would power cogeneration engines or hydrogen cells, producing electricity and heat during periods of shortage. Financial results will be increased by the income from the sale of produced oxygen. The calculations assumed that oxygen would be sold for 60% of the current price of technical oxygen. Abandoning the combustion of hydrogen in favor of its wholesale or retail sale would significantly improve the operating parameters of the closed-circuit mine water pumping station energy self-sufficiency project. All variants use a 1 MWh battery energy storage facility. This energy storage will buffer residual electricity production, e.g., in the event of partially cloudy conditions. The stored energy will be used to stabilize the power supply to the pumping station equipment or to power the electrolysis process. According to experts' opinion, a reduction in the purchase price of electricity is expected in 2024. The calculations simulated a hypothetical price reduction of approximately 18 percentage points. The forecast results are presented in Table 4.

In all variants, with constant investment outlays, there was a reduction in estimated savings when purchasing electricity by approximately 10 percentage points. The expenditure return period resulting directly from savings increased by approximately 1 year compared to the calculations for the energy purchase price from the fourth quarter of 2023. Due to the lower costs of purchasing energy from the local supplier, the coverage of the pumping station's energy demand increased significantly by 9 to 18 percentage points, and the coverage of the company's energy demand increased by approximately 0.3 percentage points. Further reduction in the purchase price of electricity would further improve the energy efficiency of the system.

Hypothetically, but very probably, the reduction in the purchase price of electricity in 2024 will result in significant overproduction of electricity. One of the conclusions of an excessive increase in the coverage of energy demand for the analyzed pumping station may consider reducing the size of the photovoltaic farm with a simultaneous reduction in the necessary expenditure on the modernization of the pumping station. Table 5 presents the forecast of the operating parameters of the analyzed pumping station in variant III with the construction of the Mine Water Treatment Station (MWTS) and the installation for collecting rainwater and process water after reducing the area of the photovoltaic farm.

Table 4. Forecasted parameters of the closed-circuit pumping station project for a hypothetical reduction in electricity purchase prices—variants I, II, and III.

A	B	C	D	E
Variant	I	II	III	
Estimated reduction in the electricity purchase costs	0.068	0.089	0.095	[multiple of expenditure]
Total expenditure	1.00	1.37	1.39	
Expenditure return period	14.7	15.5	14.6	[years]
Energy needs cover of the pumping station	109	111	119	[%]
Energy needs cover of the company	2.37	3.08	3.29	[%]
Equivalent reduction in CO_2 emissions	5632	7330	7836	[Mg CO_2/year]
Auto-consumption of generated electricity	42.8	45.6	46.3	[%]
Maintenance of workplaces	8	14	17	[item]

Table 5. Forecasted parameters of an investment limitation in variant III of the closed-circuit pumping stations for a hypothetical reduction in electricity purchase prices.

A	B	C
Estimated reduction in the electricity purchase costs	0.080	[multiple of expenditure on the basic variant]
Total expenditure	1.14	
Expenditure return period	14.3	[years]
Energy needs cover of the pumping station	99.67	[%]
Energy needs cover of the company	2.76	[%]
Equivalent reduction in CO_2 emissions	6565	[Mg CO_2/year]
Auto-consumption of generated electricity	54.17	[%]
Maintenance of workplaces	17	[items]

The farm area was selected in such a way that the installation would cover the current energy demand of the pumping station with a simulated hypothetical reduction in the purchase price of electricity of approximately 18% compared to the price in the fourth quarter of 2023. For such assumptions, the investment 25 percentage points lower than previously expected for this variant would be sufficient [49,50]. Reducing expenditure only slightly reduced the expenditure return period [22,51,52]. However, it should be taken into account that such an action would involve the risk of potential loss of the project's energy independence after a possible further increase in energy prices.

4. Conclusions

In the face of the global challenge of the deepening shortage of drinking water, it is not justified to use excessively conventional water supply sources (tap water) for industrial purposes. The global water crisis forced the search for new sources of water supply for technological purposes. Undeveloped water sources for food or technological purposes include, among others, rainwater and mine water, which, after treatment, can be the source of water fulfilling the electrolyzer. The current recognition of rainwater and process water treatment technologies allows us to select technological processes so that the system operates safely, reliably, and permanently. The only limitation is the cost of treatment.

For the effective implementation of the hydrogen economy, it is necessary to conduct R&D and, consequently, implement the developed solutions and technologies in energy, transport, and industry. One of the aspects is to conduct research in the area of methods of obtaining and treating water, which will serve as a source of hydrogen and oxygen obtained in the electrolysis process. Electrolyzers powered by energy from renewable sources allow the production of the so-called green hydrogen as a medium for the long-term and stable storage of generated surpluses of "green" energy. The source of water for the electrolysis process can be rainwater treatment and technological water treatment, respectively.

The analyzed pumping station is one of 19 pumping stations located in the Silesian agglomeration. A network of pumping stations belonging to SRK S.A. protects active mines and the ground surface against flooding. The largest component of the operating costs of each pumping station are fees for the purchase of electricity. The answer is to use renewable energy sources to support conventional power supply. The effective use of renewable energy sources requires the use of energy storage. The development and implementation of efficient methods of generating and storing energy is an important task for the company's operations. These activities are also part of projects increasing the share of energy obtained from renewable sources in Poland's energy mix. Innovative energy generation and storage systems in liquidated mines are attractive both ecologically and economically.

As a result of the research, three variants of the concept of the pilot solution for energy self-sufficiency in the example of the mine water pumping station were designed. All variants assume the conversion of energy surpluses produced by a photovoltaic farm built in the pumping station into hydrogen. Financial results will be increased by the income from the sale of produced oxygen. The calculations assumed that oxygen would be sold for 60% of the current price of technical oxygen. All variants use a 1 MWh battery energy storage facility. This energy storage will buffer residual electricity production, e.g., in the event of partially cloudy conditions. After the battery energy storage is at least partially filled, the stored energy will be used to stabilize the power supply to the pumping station equipment or the electrolysis process.

The assessment of the adopted variants for the modernization of the pumping station was aimed at presenting a comprehensive assessment of the proposed actions, taking into account possible variants. The result of the analysis is only information that will enable the selection of the optimal variant.

All presented technical solutions are economically justified and recommended for implementation due to the increase in energy security and security of drinking water supplies. The decision on the scale of the project depends on financial possibilities and arrangements with local governments. The implementation of all proposed projects requires expenditure that should be returned after a period of 13 to 15 years (Tables 1–5). Modernization of the existing pumping station infrastructure combined with new technologies that serve the local community will be a self-financing solution with a positive social and image response.

An important aspect in this case is social education in the field of water use, particularly in the implementation of demonstration and pilot projects showing local communities unconventional ways of water treatment before their actual use as a water source, both as a source of technological and process water, as well as water intended for human consumption.

Author Contributions: Conceptualization, M.M., A.C., R.D. and A.S.; methodology, M.M., A.C. and A.S.; formal analysis, M.M., R.D. and A.C.; investigation, M.M. and A.C.; writing—original draft preparation, M.M. and A.C.; writing—review and editing, M.M. and A.C.; visualization, 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 company Mines Restructuring Company (Spółka Restrukturyzacji Kopalń S.A.). 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. Badakhshan, N.; Shahriar, K.; Afraei, S.; Bakhtavar, E. Evaluating the impacts of the transition from open-pit to underground mining on sustainable development indexes. *J. Sustain. Min.* **2023**, *22*, 154–168. [CrossRef]
2. Biały, W.; Grebski, W.; Galecki, G.; Kaniak, W. Environmental Impact of The Mechanical Coal Processing Plant. *Acta Montan. Slovaca* **2020**, *25*, 139. [CrossRef]
3. Hapuwatte, B.M.; Jawahir, I.S. Closed-loop sustainable product design for circular economy. *J. Ind. Ecol.* **2021**, *25*, 1430–1446. [CrossRef]
4. Howaniec, N.; Zdeb, J.; Gogola, K.; Smoliński, A. Utilization of Carbon Dioxide and Fluidized Bed Fly Ash in Post-Industrial Land Remediation. *Materials* **2023**, *16*, 4572. [CrossRef] [PubMed]
5. 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]
6. Gawęda, A.; Sajnóg, A. Cross-sectoral detection of the Return on Equity determinants based on the 7-factor DuPont model. *Stud. Prawno-Ekon.* **2020**, *114*, 217–234. [CrossRef]
7. Bondarenko, V.; Salieiev, I.; Kovalevska, I.; Chervatiuk, V.; Malashkevych, D.; Shyshov, M.; Chernyak, V. A new concept for complex mining of mineral raw material resources from DTEK coal mines based on sustainable development and ESG strategy. *Min. Miner. Deposits* **2023**, *17*, 1–16. [CrossRef]
8. Doorga, J.R.S.; Hall, J.W.; Eyre, N. Geospatial multi-criteria analysis for identifying optimum wind and solar sites in Africa: Towards effective power sector decarbonization. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112107. [CrossRef]
9. Hai, T.; Chauhan, B.S.; Mahariq, I.; Fouad, H.; El-Shafai, W. Assessing and optimizing a cutting-edge renewable-driven system for green hydrogen production/utilization, highlighting techno-economic and sustainability aspects. *Int. J. Hydrogen Energy* **2024**, *61*, 934–948. [CrossRef]
10. Shchegolkov, A.V.; Shchegolkov, A.V.; Zemtsova, N.V.; Stanishevskiy, Y.M.; Vetcher, A.A. Recent Advantages on Waste Management in Hydrogen Industry. *Polymers* **2022**, *14*, 4992. [CrossRef]
11. Cho, H.H.; Strezov, V.; Evans, T.J. A review on global warming potential, challenges and opportunities of renewable hydrogen production technologies. *Sustain. Mater. Technol.* **2023**, *35*, e00567. [CrossRef]
12. Wilkinson, J.; Mays, T.; McManus, M. Review and meta-analysis of recent life cycle assessments of hydrogen production. *Clean. Environ. Syst.* **2023**, *9*, 100116. [CrossRef]
13. Belhadi, A.; Kamble, S.S.; Jabbour, C.J.C.; Mani, V.; Khan, S.A.R.; Touriki, F.E. A self-assessment tool for evaluating the integration of circular economy and industry 4.0 principles in closed-loop supply chains. *Int. J. Prod. Econ.* **2022**, *245*, 108372. [CrossRef]
14. Lieder, M.; Rashid, A. Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *J. Clean. Prod.* **2016**, *115*, 36–51. [CrossRef]
15. Chmielewska, I.; Chałupnik, S.; Wysocka, M.; Smoliński, A. Radium measurements in bottled natural mineral-, spring- and medicinal waters from Poland. *Water Resour. Ind.* **2020**, *24*, 100133. [CrossRef]
16. 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]
17. 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]
18. Chand, K.; Paladino, O. Recent developments of membranes and electrocatalysts for the hydrogen production by anion exchange membrane water electrolysers: A review. *Arab. J. Chem.* **2023**, *16*, 104451. [CrossRef]
19. Salari, A.; Hakkaki-Fard, A.; Jalalidil, A. Hydrogen production performance of a photovoltaic thermal system coupled with a proton exchange membrane electrolysis cell. *Int. J. Hydrogen Energy* **2022**, *47*, 4472–4488. [CrossRef]
20. Li, C.; Baek, J.-B. The promise of hydrogen production from alkaline anion exchange membrane electrolyzers. *Nano Energy* **2021**, *87*, 106162. [CrossRef]
21. Narbaitz, R.M.; Chartrand, Z.G.; Sartaj, M.; Downey, J. Ammonia-Ca-K competitive ion-exchange on zeolites in mining wastewater treatment: Batch regeneration and column performance. *J. Sustain. Min.* **2020**, *19*, 1–71. [CrossRef]
22. Gajdzik, B.; Sujova, E.; Małysa, T.; Biały, W. The accident rate in Polish mining. Current status and forecast. *Acta Montan. Slovaca* **2022**, *27*, 620–634. [CrossRef]
23. 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]
24. 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]
25. 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]
26. Chmiela, A.; Smoliło, J. The method of preliminary estimation of outlays and time necessary to carry out the processes of liquidation of a mining plant. *Min. Mach.* **2023**, *41*, 2719–3306. [CrossRef]
27. Kicki, J.; Dyczko, A. The concept of automation and monitoring of the production process in an underground mine. *New Tech. Technol. Min.* **2010**, 245–253. [CrossRef]

28. Mucha, Z.; Generowicz, A.; Wójcik, 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]
29. Prusek, S.; Turek, M. Improving the Management of a Mining Enterprise a Condition for Increasing the Efficiency of Hard Coal Production. *J. Pol. Miner. Eng. Soc.* **2018**. [CrossRef]
30. Kamiński, P.; Niedbalski, Z.; Małkowski, P.; Bozic, D. Application of composite materials in underground mining industry–foreshaft closing platform. *Min. Mach.* **2022**, *40*, 19–31. [CrossRef]
31. Mhlongo, S.E. Evaluating the post-mining land uses of former mine sites for sustainable purposes in South Africa. *J. Sustain. Min.* **2023**, *22*, 110–127. [CrossRef]
32. Mhlongo, S.E.; Amponsah-Dacosta, F. A review of problems and solutions of abandoned mines in South Africa. *Int. J. Mining, Reclam. Environ.* **2016**, *30*, 279–294. [CrossRef]
33. 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. Geomech. Abstr.* **2020**, *126*, 104175. [CrossRef]
34. Schoenmaker, D.; Schramade, W. *Principles of Sustainable Finance*; Oxford University Press: London, UK, 2019.
35. Fidalgo-Valverde, G.; Menéndez-Díaz, A.; Krzemień, A.; Riesgo-Fernández, P.; Sierra, A.L.M. Environmental risk assessment in coal mining with methane degassing. *MATEC Web Conf.* **2023**, *389*, 00039. [CrossRef]
36. Kim, J.C.; Kim, J.; Park, J.C.; Ahn, S.H.; Kim, D.-W. Ru2P nanofibers for high-performance anion exchange membrane water electrolyzer. *Chem. Eng. J.* **2021**, *420*, 130491. [CrossRef]
37. Krzemień, A.; Fernández, J.J.; Fernández, P.R.; Valverde, G.F.; Garcia-Cortes, S. Restoring Coal Mining-Affected Areas: The Missing Ecosystem Services. *Int. J. Environ. Res. Public Health* **2022**, *19*, 14200. [CrossRef]
38. Krzemień, A.; Fernández, J.J.; Fernández, P.R.; Valverde, G.F.; 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]
39. 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]
40. 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]
41. Woszczyński, 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]
42. 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]
43. Wysocka, M.; Chałupnik, 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. *Mine Water Environ.* **2019**, *38*, 581–589. [CrossRef]
44. Esquivel-Patiño, G.G.; Nápoles-Rivera, F. Environmental and energetic analysis of coupling a biogas combined cycle power plant with carbon capture, organic Rankine cycles and CO_2 utilization processes. *J. Environ. Manag.* **2021**, *300*, 113746. [CrossRef] [PubMed]
45. 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]
46. Liu, L.; Bai, L.; Liu, Z.; Miao, S.; Pan, J.; Shen, L.; Shi, Y.; Li, N. Side-chain structural engineering on poly(terphenyl piperidinium) anion exchange membrane for water electrolysers. *J. Membr. Sci.* **2023**, *665*, 121135. [CrossRef]
47. Petlovanyi, V.; Malashkevych, D.S.; Sai, K.S. The new approach to creating progressive and low-waste mining technology for thin coal seams. *J. Geol. Geogr. Geoecol.* **2020**, *29*, 765–775. [CrossRef]
48. Wojtacha-Rychter, K.; Kucharski, P.; Smoliński, A. Conventional and alternative sources of thermal energy in the production of cement an impact on CO_2 emission. *Energies* **2021**, *14*, 1539. [CrossRef]
49. Gawęda, A. Sustainability Reporting: Case of European Stock Companies. *Eur. J. Sustain. Dev.* **2021**, *10*, 41. [CrossRef]
50. Gawęda, A.; Złoty, M. The impact of ESG ratings on the market performance of commodity stock sector before and during the COVID-19 pandemic. *Ekon. Prawo. Econ. Law* **2023**, *22*, 531–553. [CrossRef]
51. Gawęda, A. ESG Rating and Market Valuation of the Firm: Sector Approach. *Eur. J. Sustain. Dev.* **2022**, *11*, 91. [CrossRef]
52. Gajdzik, B.; Wolniak, R.; Nagaj, R.; Grebski, W.; Romanyshyn, T. Barriers to Renewable Energy Source (RES) Installations as Determinants of Energy Consumption in EU Countries. *Energies* **2023**, *16*, 7364. [CrossRef]