

Article

Performance Analysis of a Solar-Powered Pulverizing Aerator

Andrzej Osuch ¹, Ewa Osuch ^{1,*} and Piotr Rybacki ²

¹ Department of Biosystems Engineering, Faculty of Environmental and Mechanical Engineering, Poznan University of Life Sciences, Wojska Polskiego 50, 60-637 Poznan, Poland; andrzej.osuch@up.poznan.pl

² Department of Agronomy, Faculty of Agronomy, Horticulture and Biotechnology, Poznan University of Life Sciences, Dojazd 11, 60-632 Poznan, Poland; piotr.rybacki@up.poznan.pl

* Correspondence: ewa.osuch@up.poznan.pl

Abstract: The global energy crisis is associated with the need to search for low-energy technical solutions. Such solutions are also introduced in the field of protection and restoration of surface waters. The aim of this work was to determine the efficiency of the AS15000 pulverizing aerator powered by solar energy. The innovative solutions of the aerator presented in this manuscript are subject to a patent application. A simulation was carried out taking into account the efficiency of the aerator pump and the sunlight conditions for the indicated location. The analysis was carried out for the location of an artificial reservoir—Zalew Średzki in Środa Wielkopolska (Poland). The simulation showed that during 6515 h of aerator operation, the pulverizing system pumped as much as 97,725 m³ of lake water. The amount of pure oxygen introduced into the water during the operation of the device can be as much as 1074.98 kg. The minimum daily value of sunlight enabling continuous operation of the device (24 h a day) with maximum efficiency is 1.43 kW/m². Deoxygenated water in the pulverizing aeration process is taken from the bottom zone, transported to the surface and sprayed in the atmospheric air. Oxygenated water is intercepted and discharged to the bottom zone. Developing artificial aeration methods for lakes in combination with renewable energy sources is very important for improving water quality. The use of solar power allows the device to be used when it is far from the power infrastructure. This also allows the installation of aerators in the middle of the lake. In accordance with the Water Framework Directive, we should strive to improve the water quality of many European lakes as quickly as possible.



Citation: Osuch, A.; Osuch, E.; Rybacki, P. Performance Analysis of a Solar-Powered Pulverizing Aerator. *Energies* **2024**, *17*, 6321. <https://doi.org/10.3390/en17246321>

Academic Editor: Nikolaos K. Koukoulas

Received: 29 October 2024

Revised: 4 December 2024

Accepted: 13 December 2024

Published: 15 December 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: lake restoration; artificial water aeration; use of solar energy in lake restoration

1. Introduction

The state of lakes in Poland and around the world has deteriorated significantly in recent years, which requires scientists and engineers to seek new methods of protecting and restoring surface waters. The intensive development of industry, agriculture, and tourism puts aquatic ecosystems under enormous pressure. Some ecosystems resist attacks for a long time, while others die, creating highly eutrophic reservoirs [1,2].

Sources of water pollution can be divided into natural and artificial, which can then be divided into point, surface (area) and linear [3,4]. Point sources of pollution include, in particular, municipal and industrial sewage treatment plants, waste disposal sites and storage facilities for hazardous substances. In the case of surface pollution, area runoff from agricultural and urban areas is mainly taken into account, and linear pollution is classified as coming mainly from road and rail communication routes [5–7]. The natural sources of surface water pollution include the presence of some microbiological organisms; acid precipitation, which is a source of biogenic substances and promotes faster leaching of fertilizer substances from the soil, which go directly to surface waters; excessive salinity of waters; and an excessive amount of iron compounds [8,9].

The most significant problem today is artificial pollution, which contributes to a very dangerous process for water: anthropogenic eutrophication. In Europe, compared to other

sources, the largest amounts of pollutants containing biogenic compounds enter water from agricultural areas, mainly through surface runoff, but also from uncontrolled discharges of municipal sewage, including domestic sewage. Particularly dangerous are scattered areas, which are not covered by municipal sewage systems [10,11]. During the eutrophication process, due to the large amount of biogenic substances in the water, the development of phytoplankton organisms significantly accelerates. Access to sunlight is blocked by algae, which means that macrophytes from deeper layers of water do not receive enough of it and die. The species structure of aquatic plants changes. The dominance of certain species, usually cyanobacteria, begins in the reservoir. Dying planktonic organisms lead to a decrease in the amount of oxygen dissolved in water, which in turn leads to a decrease in biodiversity in the water body and the number of noble and desirable species. Some species of algae produce substances that are highly toxic and dangerous to both animals and humans. In extreme cases, it can even lead to coma or death [12–15].

To sum up, anthropogenic eutrophication is currently one of the most serious threats to surface waters and one of the main environmental problems. In the European Union, 33% of water is eutrophic or hypertrophic, while, in Poland, these numbers reach 62% for rivers and 63% for lakes [9,16].

The above indicates that it is necessary to immediately implement methods for the protection and restoration of water reservoirs [17,18]. The currently used methods for the restoration of water reservoirs can be divided into biological, chemical and technical methods [2,10]. Biological methods mainly involve controlling the population of flora and fauna in a water reservoir. [19,20]. Unfortunately, introducing barley straw or effective microorganisms leads to a short-term improvement in water quality. In particular, effective microorganisms contribute to faster mineralization of organic matter, which, in subsequent years, results in an increased amount of bioavailable compounds, especially ammonium nitrogen and phosphates. Chemical methods include treatments related to the use of PAX coagulants based on Al^{3+} , PIX, and Fe^{3+} , both in the water column and bottom sediments [9]. Because coagulants based on aluminum compounds, in the case of a change in pH, can lead to the release of toxic compounds, they are not recommended by many scientists [21–23].

Technical methods of restoration include the removal of bottom sediments, which is a very expensive and organizationally complicated procedure [24]. Removing hypolimnion waters is a method involving placing a pipeline on the bottom of a lake or other water reservoir. Its inlet should be located in the deepest part of the lake, and its outlet at the outlet. The pipeline, operating on the principle of a hydraulic siphon, allows for the spontaneous outflow of water from the bottom [25].

Undoubtedly, one of the most important and safest technical methods is artificial aeration. Starting with compressors that inject atmospheric air under high pressure into the bottom waters through aerators that draw water from the reservoir in order to oxygenate it [2,11,16], these devices have a very diverse structure and operating principle. Aeration with thermal destratification can be carried out using a diffuser aerator, which mixes water by introducing air bubbles into the tank at the very bottom, which then rise and bring the hypolimnion water to the surface, where they mix with the epilimnion water. Diffusion itself supplies trace amounts of oxygen to the water, with the most important factor being the contact of water from the bottom of the water tank with atmospheric air after mixing [25]. In contrast to the diffuser aerator, the aerator with an axial pump is placed on the surface of the water tank, and the rotation of the screw located at the bottom of the device causes the surface water to be forced into the depths of the tank; thus, the entire volume of water is mixed and aerated and thermal stratification is disturbed [9,15]. Aerators that operate without disrupting stratification include splash aerators that operate on the principle of sucking surface water into the device using a pump and spraying it into the air [11,12,26]. Aerators with total and partial lifting are fully or completely immersed in water. Aeration takes place inside the device. They operate on the principle of introducing compressed air from the bottom of the device, mixing it with the hypolimnion waters and lifting the aerated waters towards the surface. In aerators with partial lifting, the aerated water is

lifted and then returned below the water table, but there is no contact with atmospheric air [9,27]. Aerators with total lifting provide longer contact of the hypolimnion waters with air bubbles and atmospheric air. This allows for better oxygenation of the waters than in the case of devices with partial lifting [25,28]. An important stage of the artificial aeration of water is the introduction of pulverization aeration, the so-called Podsiadłowski method [16,18]. Pulverization aeration technology is considered to be a development of total lift aeration. In this method, water is collected from the bottom of the reservoir using a pump and then supplied through pipes to the pulverization segment, where it is mechanically crushed and atomized. Usually, for this purpose (depending on the type of pulverization aerator), spray nozzles or paddle wheels are used. The pulverization process has a positive effect on the efficiency of gas exchange in the hypolimnion waters because H_2S is replaced by O_2 during aeration [11,12,16]. Both devices standing on land and floating devices directly above the polluted lake depth can be used for pulverization aeration. These can be devices powered both from the power grid and directly from renewable sources (in particular wind and sun) [25]. The Podsiadłowski pulverizing aerator is a device floating on the surface of a water reservoir, powered by a Savonius wind engine and wind energy (later hybrid power supply, combining the simultaneous use of wind and solar energy). The use of such a power source results from the process of anthropopression, rising energy prices and the desire to use nature itself to a greater extent than before for the purpose of lake restoration by powering the aerator with a renewable energy source. The rotor engine used in the aerator is characterized by durability and simple construction [12,29]. The latest technical solution for pulverizing aeration is a technology that only uses solar energy in the pulverizing aeration process, which was developed by Osuch et al., supporting the bio-dredge process [9].

Construction and operating principle of a solar-powered pulverizing aerator, the so-called Osuch AS15000 aerator.

The discussed aerator (Figure 1) is powered by six photovoltaic panels with a power of not less than 300 Wp and has three panels arranged on each side of the aerator and attached to the frame. The aerator draws water from the bottom zone of the lake using a suction pipe, using a 0.1 kW pump. The deoxygenated water then goes to the spray nozzle located in the center of the device, which pulverizes the liquid taken from the hypolimnion. The aerated water falls onto the panels, cooling them. The photovoltaic panels are attached at a slight angle to the frame, allowing the water to flow freely into the discharge gutter, which is screwed to the frame from the bottom and runs through the center of the device along its entire length. Then, it is drained from the gutter using discharge pipes to a set depth. The frame of the device is mounted on four floats. The twilight sensor on the device turns on the 9 W lighting at night and turns it off at dawn. The lighting has two functions: safety, as the aerator is visible from a distance at night, and visual effect, as the light illuminates the water stream, creating visual effects. The system is powered by two (24 V) or four (12 V) AGM, GEL or $LiFePO_4$ batteries with a total capacity of 4.8 kWh.

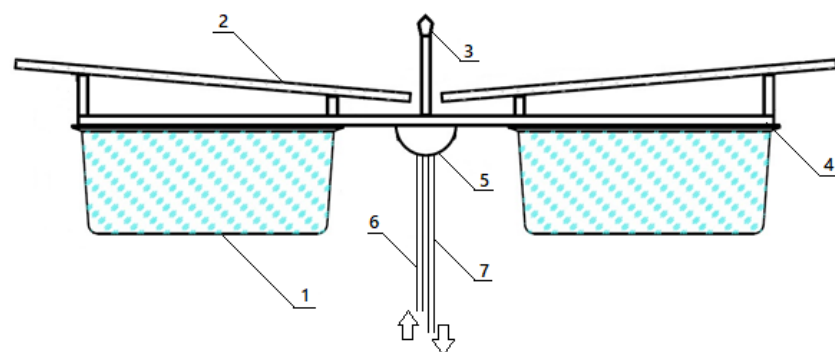


Figure 1. Schematic diagram of the solar-powered pulverizing aerator (1—buoyancy floats—the buoyancy foam filling is marked in blue, 2—photovoltaic panels, 3—pulverizing atomizer, 4—frame, 5—aerated water collector, 6—suction pipes, 7—pressure pipes).

2. Materials and Methods

The aim of the work undertaken was to conduct an analysis of the performance of the AS15000 solar-powered pulverizing aerator in the period from the beginning of March to the end of November (this period includes spring, summer and autumn). The simulation was based on the sunlight conditions for the location of the Średzki Reservoir in Środa Wielkopolska (Poland). The simulation takes into account the following parameters: pump operation time during the period of use of the device, the amount of oxygenated water and the amount of pure oxygen introduced into the water reservoir in the assumed period.

The most important parameters of the AS15000 solar-powered pulverizing aerator are indicated below.

- 6 × 330 Wp photovoltaic panels;
- 4 × 12 V, 100 Ah GEL batteries;
- 100 W water pump, 24 V supply voltage, efficiency $15 \frac{\text{m}^3}{\text{h}}$;
- 9 W lighting with 24 V supply voltage.

The amount of pure oxygen introduced into the water (only applies to oxygen-free water taken by the device from the bottom zone of the lake) is on average $11 \frac{\text{mg}}{\text{dm}^3}$ of water taken by the aerator from the bottom zone. The given value of oxygen introduced into the water is true for deoxygenated hypolimnion waters. In the case of the oxygenation of waters containing a higher amount of oxygen, this value would be lower.

Data on insolation and the length of day and night were obtained for the geographical location: Poland, Wielkopolska Province, Środa Wielkopolska, Lake Średzkie, with the following geographical coordinates: 52.239, 17.291. Lake Średzkie was selected as the research object due to the observed occurrence of hypoxia in this water reservoir (in 2022, several tons of dead fish were fished out of the reservoir), i.e., a decrease in the amount of oxygen soluble in water, which may be associated with the mass extinction of aerobic organisms living in the water reservoir in the absence of appropriate aeration treatments. Due to the rarity of using photovoltaic panels as a power source for a pulverizing aerator, a difficulty was encountered in determining their efficiency coefficient under lake water cooling conditions. Due to the continuous cooling of the photovoltaic installation with cold waters of the hypolimnion, losses related to heating of the panels were considered negligible, and the same process was carried out in the case of losses resulting from panel dirt, as they are automatically washed 24 h a day. Losses on cables were also omitted due to the use of the minimum length of cabling in the device (maximum length 2.5 m). However, losses resulting from low solar radiation intensity were taken into account, which were assumed at the level of 3%. Due to the assumption of long-term use of the device, losses resulting from aging of materials were also assumed for the calculations. According to the characteristics of photovoltaic panels, these losses should not exceed 7% until the tenth year of use. After adding up the losses included in the device, the efficiency factor for photovoltaic panels was assumed at the level of 90%. Due to the small and mirror-like inclination angles of the photovoltaic panels powering the aerator (Figure 2) and the fact that the device rotates around its own axis, the correction factor, i.e., the factor defining the inclination of the photovoltaic panels to the vertical and their deviation from the south, was assumed as 1; therefore, the system was treated as completely horizontal.

The calculations began with consideration of the parameters of a battery pack consisting of four batteries, and then the maximum capacity of the battery pack expressed in kilowatt-hours was calculated. This unit was adopted to simplify the calculations.

The minimum daily power required to power the aerator for one day was determined. Each month in which the average daily value of insolation was sufficient to obtain at least the minimum required power to power the device for 24 h was classified, without further calculations, as a month in which the device worked without interruption. For the remaining months, additional calculations were made to show the device's average hours of operation for a given month, which does not meet the lower limit of data required to power the device 24 h a day.



Figure 2. Pulverizing aerator AS15000.

Calculations were made taking into account the numerical and percentage operating time of the device, the amount of water subjected to the aeration process and the amount of pure oxygen introduced into the water in the aeration process.

Data on insolation were obtained from the PVGIS system. Data were obtained and divided into monthly averages from the years 2011 to 2020. The data taken into account were narrowed down to those that coincided with the months of operation of the tested device. The average was taken from the insolation values for each month within the scope of the study over the decade, as shown in Table 1.

Table 1. Average monthly insolation of Lake Średzkie in the months from March to November in the years 2011–2020.

Month	March	April	May	June	July	August	September	October	November
Average monthly insolation [kWh/m ²]	92.36	134.39	148.68	143.21	138.96	147.88	107.77	71.77	37.61

Due to the use of a twilight sensor in the device, which affects the operating hours of the lighting, it was necessary to obtain data on the hours of dawn and dusk in order to obtain accurate results for the analysis of the aerator's efficiency because the power drawn by the device from dusk to dawn increases slightly. Using the website (www.timeanddate.com, accessed on 12 December 2024), detailed data on the time of occurrence for the selected date and location of sunrises and sunsets was obtained. Using this tool, a table was developed showing the average length of day and night during the year in each analyzed month for the city of Środa Wielkopolska (Table 2).

Table 2. Average monthly length of day and night in the months studied.

Month	Sunrise Time	Sunset Time	Day Length	Night Length
March	6:30	18:00	11 h 30 min	12 h 30 min
April	6:15	19:30	13 h 15 min	10 h 45 min
May	5:15	20:30	15 h 15 min	8 h 45 min
June	4:30	21:15	16 h 45 min	7 h 15 min
July	4:45	21:00	16 h 15 min	7 h 45 min
August	5:30	20:15	14 h 45 min	9 h 15 min

Table 2. Cont.

Month	Sunrise Time	Sunset Time	Day Length	Night Length
September	6:30	19:00	12 h 30 min	11 h 30 min
October	7:15	18:00	10 h 45 min	13 h 15 min
November	7:15	16:00	8 h 45 min	15 h 15 min

3. Results

3.1. Calculation of the Energy Demand of the Aerator

This manuscript includes basic calculations of the device's operating parameters and the amount of energy required for daily power supply and also calculates the aerator's operating time for each month in which the minimum daily amount of energy is not generated.

(a) Battery pack parameters:

From four 12 V batteries with a capacity of 100 Ah, two batteries were connected in series to obtain two pairs of batteries. The parameters characterizing each pair were 24 V and 100 Ah. Then, both pairs were connected in parallel. As a result of this procedure, a battery system with total parameters of 24 V and 200 Ah was finally obtained.

(b) Maximum capacity of the battery assembly:

To facilitate further calculations, the unit of battery capacity was assumed as kWh instead of the Ah specified by the manufacturer. This procedure was used due to the fact that the data regarding the power consumed by the aerator components and the data regarding sunlight are expressed in watts.

$$K \text{ (Wh)} = U \times K(\text{Ah})$$

where K (Wh)—Capacity expressed in watt-hours;

U (V)—Voltage of electric current;

I (Ah)—Capacity expressed in ampere-hours.

$$K = 200 \text{ Ah} \times 24 \text{ V} = 4800 \text{ Wh} = 4.8 \text{ kWh}$$

The maximum capacity of the battery pack used in the aerator was calculated to be 4.8 kWh.

- (c) Maximum amount of energy drawn by the aerator per day: To calculate the minimum amount of electrical energy that must be stored in the batteries to power the device for at least 24 h, knowledge of the daily energy consumption of the tested object is required. During the day, the only device drawing energy from the batteries is a 100 W pump. Due to the use of a twilight sensor, which switches on the aerator lighting, at night, the energy consumption after dark is affected by the pump and 9 W lighting. In order to determine the maximum energy drawn by the device and thus the minimum energy that must be produced by the aerator to maintain continuous operation for one day, the most unfavorable lighting conditions were assumed from the nine-month period studied. Data establishing November as the month with the longest night lasting 15 h 15 min and day lasting 8 h 45 min were obtained from Table 2.

$$E_{Amax} = E_d + E_n$$

where

E_{Amax} —Maximum energy consumed by the aerator per day;

E_d —Energy consumed by the device in one day;

E_n —Energy consumed by the device in one night.

where

$$E_d = t_d \times P_d$$

where

t_d —Duration of the day;

P_d —Power consumed by the device during the day for one hour

Where.

$$E_n = t_n \times P_n$$

where

t_n —Duration of the night;

P_n —Power consumed by the device during the night for one hour.

After expanding the formula for E_{Amax} and substituting the data, the equation was obtained:

$$E_{Amax} = 8.75 \text{ h} \times 100 \text{ W} + 15.25 \text{ h} \times 109 \text{ W} = 253.25 \text{ Wh}$$

$$E_{Amax} = 2537.25 \text{ Wh} \sim 2.54 \text{ kWh}$$

The results obtained therefore determine the minimum energy that the aerator must produce to power its components for 24 h is 2.54 kWh.

- (d) Minimum monthly value of insolation needed to power the pulverizing aerator for one day: The information obtained from the calculations performed in sub-item c may allow for a significant simplification of the calculations required to analyze the efficiency of the solar-powered aerator. For this purpose, it is necessary to calculate the monthly value of insolation, which allows for the production of an amount of energy equal to at least 2.54 kWh in one day using six photovoltaic panels with a nominal power of 330 Wp. For this purpose, a transformation of the formula for the actual energy yield from the photovoltaic installation was used so that it allows for the determination of the minimum value to power the aerator for 24 h. The transformed formula and calculations are as follows:

$$E_{Nmin} = \frac{E_{Amax}}{W_{Kor} \times P_m \times i_m \times W_w}$$

where

E_{Nmin} —The minimum daily solar radiation value required to power the device for 24 h;

W_{Kor} —Photovoltaic installation correction factor;

P_m —Power of a single module;

i_m —Number of modules;

W_w —Photovoltaic installation efficiency factor.

$$E_{Nmin} = \frac{2.54 \text{ kWh}}{1 \times 0.33 \text{ kWp} \times 6 \times 0.9} = 1.43 \text{ h}$$

The result was recorded in the above form due to the desire to maintain the correct aesthetics of the units in the calculations. However, it can be read in two ways, namely as 1.43 h, i.e., less than 86 min of sunlight with a power of 1 kW/m², and also as the total value of daily sunlight of at least 1.43 kW/m² during the day. The second form will be adopted for calculations due to the ease of calculations and convenience of their presentation.

The result obtained therefore means that each month in which the average daily value of sunlight was greater than or equal to 1.43 kW/m² can be considered a month in which the aerator pump worked without any interruption in the power supply.

3.2. Aerator Efficiency Calculations

Calculations for averaged data: After comparing the averaged data with the required minimum daily value of sunlight for each month in the tested range, it was found that in the period from the beginning of March to the end of October, the aerator will operate continuously. Only November was taken into account for the calculation of the aerator's operating time, and the average daily insolation is only 1.25 kWh/m².

Due to the fact that the E_{Amax} parameter was calculated for the conditions and durations of day and night in November, the calculation of the daily demand for the month considered in this subsection can be omitted because it will be the equivalent of the mentioned parameter and therefore will be 2.54 kW/m^2 . The actual energy yield for the device in November was calculated using the following formula:

$$E_{rz} = E_n \times W_{Kor} \times P_m \times i_m \times W_w$$

where

E_{rz} —Actual daily energy yield;

E_n —Daily solar radiation value.

$$E_{rz} = 1.25 \text{ kWh/m}^2 \times 1 \times 0.33 \text{ kWp} \times 6 \times 0.9 = 2.23 \text{ kWh}$$

The obtained result shows that the tested aerator operating in the conditions of Lake Średzkie will produce an average of 2.23 kWh of electricity per day.

Due to the charging of batteries during daytime hours, the priority of daytime hours was assumed as the operating hours of the device, and any breaks in the aerator's operation will therefore be considered in the vast majority of cases within the night hours. In order to avoid negative results in the event that the aerator does not accumulate enough energy to power the pump during daytime hours, the following relationship was used:

If

$$E_{rz} \leq E_d$$

this means that the aerator did not produce and store enough energy to operate during daylight hours. In this case, the following formula should be used for calculation:

$$t_W = \frac{E_{rz}}{P_d}$$

where

t_W —Daily working time of the aerator in hours.

However, if

$$E_{rz} > E_d$$

this means that the aerator has produced and stored enough energy to operate at least during all daylight hours. In this case, the device's nighttime operation time must be considered and then added to the daily operating time, which is expressed by the formula:

$$t_W = \frac{E_{rz} - E_d}{P_n} + t_d$$

After deriving the dependencies and formulas, the calculation of the average aerator operating time for each month was started. First, it was checked which dependency was true.

$$2.23 \text{ kWh} > 0.875 \text{ kWh}$$

Next, the average daily working time was calculated in each month using the following relationship:

$$t_W = \frac{2.23 \text{ kWh} - 0.875 \text{ kWh}}{0.109 \text{ kW}} + 8.75 \text{ h} = 21.18 \text{ h}$$

Knowing the average working time of the aerator in each month, a table (Table 3) was prepared showing working times in individual months and the sum of working time in the entire period under study. In addition, knowing the hourly efficiency of the pump and the amount of pure oxygen introduced for each liter of pumped water, calculations were made

for each of these values in order to present the sum of the amount of pumped water and pure oxygen introduced into the water, as shown in Table 3.

Table 3. Results representing the aerator efficiency for averaged solar radiation data at the Średzkie Lake location.

Month	March	April	May	June	July	August	September	October	November
Working time [h]	744	720	744	720	744	744	720	744	635
Total working hours [h]	6515								
Amount of water pumped [m ³]	97,725								
Amount of pure oxygen introduced into the reservoir [kg]	1074.98								

4. Discussion

The average achievable operating time of the device in the period from the beginning of March to the end of November is 6515 h. Assuming that the maximum achievable operating time value is equal to 100%, it can be stated that the aerator achieved a result of 98.6% efficiency. These results allow us to state that the tested type of aerator is characterized by very good efficiency even in extremely unfavorable sunlight conditions. This state of affairs is very much influenced by the appropriate selection of the device's components and its construction, which significantly reduces potential energy losses associated with the use of photovoltaic panels as a power source. The total power of the used photovoltaic panels is sufficient for a significant part of its operating time to produce and store enough energy to power the aerator for at least 24 h, even in relatively unfavorable sunlight conditions. This is facilitated by the fact that the photovoltaic panels are mounted directly on the device operating on the lake. This not only helps avoid any risk of shading the panels but, as analyses have shown, it also reduces the losses generated by dirt on the photovoltaic panels and the temperature of the PV modules in the summer months to negligible values. This is because water falling on the panels washes and cools them continuously. Insufficient data on the operation of constantly sprayed photovoltaic panels, operating in conditions that are rarely encountered, made it difficult to estimate the losses generated by them and could contribute to the probable small deviation in the analyzed data from the actual performance of the device. In connection with the above, it was considered that a future comparative analysis of the operation of wet and dry panels could have a positive impact on the general knowledge base available in both the field of photovoltaics and water aeration. However, as other researchers point out, the cooling of photovoltaic panels has a significant impact on increasing the efficiency of photovoltaic panels [30–32].

Another advantage of the device, affecting its efficiency, is the fact that the components drawing energy from the batteries are appropriately selected, i.e., they operate at the same (24 V) voltage as the battery pack, which allows avoiding unnecessary elements in the device, such as a voltage converter, which generates additional losses. In addition, the pump used generates very high efficiency with low energy demand. The lighting switch-on time was limited to the necessary minimum using a twilight sensor.

To a small extent, the selection of the battery pack capacity also has a positive effect on the device's operating time in such a way that the device, when fully charged, can operate continuously for almost two days, but this is difficult to determine precisely without performing more detailed calculations. This is particularly important when there is a day with low sunlight during which the device would not normally be able to operate 24 h but the accumulated energy resource allows it. This may even contribute to a slight increase in the actual efficiency of the device compared to the presented data.

The analysis of the theoretical efficiency of a wind-powered pulverizing aerator in the conditions of Lake Góreckie using the maximum wind speed method [12] showed that the

efficiency that the device should achieve in real conditions is, on average, less than 8800 m³ of aerated water per month.

On the other hand, the analysis from 2018 carried out for the same device, but using the average wind speed method [16], showed that the average monthly efficiency of a wind-powered aerator in terms of the amount of pumped water is 8300 m³ per month.

Professor R. Konieczny claims that depending on the wind conditions occurring in a given location, the efficiency results of a wind-powered pulverizing aerator may range from 5977.8 to 13,418.4 m³ of aerated water each month [33].

According to the calculations made in this work, the average monthly efficiency of a solar-powered aerator, which also oxygenates water using pulverization technology, is 10,858 m³ of aerated water per month. This shows that a solar-powered aerator achieves comparable results to a wind-powered pulverization aerator [12,16]. However, compared to the maximum efficiency of a wind-powered aerator presented by Professor Konieczny [33], it may turn out that in areas with very good wind exposure, wind-powered pulverization aerators can achieve significantly higher efficiency.

Taking into account the popularity of the wind-powered pulverizing aerator, a solution used in Poland for years; the fact that it has been used to restore many water reservoirs; and the high interest in it over the years, which can be seen from the number of scientific publications on the subject, it was found that the solar-powered pulverizing aerator is a very future-proof device due to the following factors: ecological power supply of the device using a renewable energy source in the form of the sun, smaller size, simpler construction than the wind-powered equivalent, very high efficiency presented by the average working time result of 98.6% and almost 11 thousand cubic meters of water aerated each month.

The obtained results prove the usefulness of the tested device in terms of the restoring of eutrophic lakes and, in particular, lakes with very poor oxygen conditions.

Solar energy is also successfully used in the distillation process, including the distillation of domestic sewage [34].

5. Conclusions

The performance analysis of the solar-powered pulverizing aerator showed high efficiency of the device in the process of aerating the water reservoir in the conditions specified for the Średzkie Lake area in the months from March to November based on data from 2011 to 2020 regarding sunlight and the duration of day and night. The obtained results are as follows:

- The performance, represented in working hours, is 6515 h, i.e., 98.6% of the possible working time in the period under study;
- The performance, expressed in the amount of aerated water during the operation of the device, is 97,725 m³ of water;
- The amount of pure oxygen introduced into the water during the operation of the device is 1074.98 kg.

This research should be expanded, in particular, to include an analysis of the efficiency of water oxygenation in the pulverizing aeration process and the impact of aerators on increasing biodiversity in the aquatic ecosystem.

The presentation and analysis of the research results obtained in this work allowed the following conclusions to be drawn:

1. The solar-powered pulverizing aerator is a device capable of using solar energy to aerate the bottom layers of lake water, which significantly reduces its operating costs.
2. The minimum daily value of insolation that allows the device to operate with maximum efficiency is 1.43 kW/m².
3. It is necessary to start research on the analysis of the efficiency of dry and sprayed photovoltaic panels. The results may prove important for the development of photovoltaics and pulverizing aeration.

Author Contributions: Conceptualization, A.O. and E.O.; methodology, A.O.; software, P.R.; validation, A.O. and E.O.; formal analysis, A.O.; investigation, A.O. and E.O. resources, A.O. and O.E.; data curation, E.O.; writing—original draft preparation, A.O. and E.O.; writing—review and editing, A.O. and E.O.; visualization, A.O. and P.R.; supervision, A.O.; project administration, A.O. and E.O.; funding acquisition, A.O. and E.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are original field studies and are available from the authors on request. They were collected from the Department of Biosystems Engineering, Faculty of Environmental and Mechanical Engineering, Poznan University of Life Sciences.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Eutrophication—the process of enriching water reservoirs with biophilic elements, resulting in increased trophy, i.e., water fertility

Lake restoration—a set of methods aimed at improving the condition (“repairing”) of lake ecosystems

Hypolimnion water—lower layer in lakes

Thermal destratification—mixing water to equalize the temperature in the individual water layers

Epilimnion water- the upper layer of water in a lake

PIX—iron coagulant

PAX—aluminum coagulant

Mycrophytes—water plants plain to see

Thermal stratification—a vertical arrangement of layers of water in a lake with different temperatures

PVGIS—(Photovoltaic Geographical Information System)—a website that provides information about solar radiation and the efficiency of photovoltaic (PV) systems

References

1. Kowalczevska-Madura, K.; Dondajewska-Pielka, R.; Gołdyn, R. The Assessment of External and Internal Nutrient Loading as a Basis for Lake Management. *Water* **2022**, *14*, 2844. [\[CrossRef\]](#)
2. Podsiadłowski, S.; Osuch, E.; Przybył, J.; Osuch, A.; Buchwald, T. Pulverizing aerator in the process of lake restoration. *Ecol. Eng.* **2018**, *121*, 99–103. [\[CrossRef\]](#)
3. Zhang, Y.; Jiao, X.; Wei, Y.; Wu, H.; Pan, Z.; Liu, M.; Yuan, J.; Ni, M.; Zhou, Z.; Zeng, L.; et al. Long-Term (1990–2013) Changes and Spatial Variations of Cropland Runoff across China. *Water* **2022**, *14*, 2918. [\[CrossRef\]](#)
4. Zhang, R.; Zhao, J.; Sheng, Q.; Zhang, Y.; Ye, J. Pollution Evaluation and Health Risk Assessment of Trace Metals in Eleven Tissues of *Mylopharyngodon piceus* Collected from an Aquaculture Pond in Huzhou, near Southern Taihu Lake. *Sustainability* **2022**, *14*, 11323. [\[CrossRef\]](#)
5. Rybacki, P.; Wolna-Maruwka, A.; Osuch, A.; Grześ, Z.; Niewiadomska, A. Seasonal variability in chemical and microbiological status of bottom sediments in Lake Rusałka at removal of cyanobacterial blooms from its surface. *Pol. J. Environ. Stud.* **2020**, *29*, 1323–1330. [\[CrossRef\]](#)
6. Osuch, E.; Osuch, A.; Podsiadłowski, S.; Rybacki, P.; Mioduszevska, N. Use of Wind Energy in the Process of Lake Restoration. In *Renewable Energy Sources: Engineering, Technology, Innovation*; Wróbel, M., Jewiarz, M., Szłęk, A., Eds.; Springer Proceedings in Energy; Springer: Cham, Switzerland, 2020; pp. 551–559.
7. Rybacki, P.; Przygodziński, P.; Osuch, A.; Blecharczyk, A.; Walkowiak, R.; Osuch, E.; Kowalik, I. The Technology of Precise Application of Herbicides in Onion Field Cultivation. *Agriculture* **2021**, *11*, 577. [\[CrossRef\]](#)
8. Herkowiak, M.; Osuch, A.; Osuch, E.; Waliszewska, B.; Zając, G. Analysis of the Possibility of Management of Curly-Leaf Pondweed for Energetic Purposes. *Energies* **2021**, *14*, 5477. [\[CrossRef\]](#)
9. Lewicki, B. Performance Analysis of a Solar-Powered Pulverizing Aerator. Bachelor’s Thesis, Poznań University of Life Sciences, Poznań, Poland, 2022. (In Polish).
10. Gołdyn, R.; Szeląg-Wasielewska, E.; Kowalczevska-Madura, K.; Dondajewska, R.; Budzyńska, A.; Podsiadłowski, S.; Domek, P.; Romanowicz-Brzozowska, W. Functioning of the Lake Rusałka ecosystem in Poznań (western Poland). *Oceanol. Hydrobiol. Stud.* **2010**, *39*, 65–80. [\[CrossRef\]](#)
11. Podsiadłowski, S. Method of precise phosphorus in activation in lake waters. *Limnol. Rev.* **2008**, *8*, 3–8.

12. Osuch, E.; Osuch, A.; Rybacki, P.; Przybylak, A. Analysis of the Theoretical Performance of the Wind-Driven Pulverizing Aerator in the Conditions of Góreckie Lake—Maximum Wind Speed Method. *Energies* **2020**, *13*, 502. [\[CrossRef\]](#)
13. Dondajewska, R.; Kowalczyńska-Madura, K.; Gołdyn, R.; Kozak, A.; Messyasz, B.; Cerbin, S. Long-Term Water Quality Changes as a Result of a Sustainable Restoration—A Case Study of Dimictic Lake Durowskie. *Water* **2019**, *11*, 616. [\[CrossRef\]](#)
14. Rosińska, J.; Kozak, A.; Dondajewska, R.; Gołdyn, R. Cyanobacteria blooms before and during the restoration process of a shallow urban lake. *J. Environ. Manag.* **2017**, *198*, 340–347. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Kowalczyńska-Madura, K.; Gołdyn, R. Antropogenic changes in water quality in Swarzędzkie Lake (West Poland). *Limnol. Rev.* **2006**, *6*, 147–154.
16. Osuch, A.; Osuch, E.; Podsiadłowski, S.; Rybacki, P. Analysis of Performance of the Wind-Driven Pulverizing Aerator Based on Average Wind Speeds in the Conditions of Góreckie Lake. *Energies* **2021**, *14*, 2796. [\[CrossRef\]](#)
17. Podsiadłowski, S.; Gołdyn, R. Methods for sustainable lake restoration. *Wielkop. Ecol. Bull.* **2009**, *3*, 2–4. (In Polish)
18. Osuch, E.; Osuch, A.; Podsiadłowski, S.; Piechnik, L.; Chwirot, D. Project of coagulant dispenser in pulverization aerator with wind drive. *J. Ecol. Eng.* **2017**, *18*, 192–198. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Klapper, H. Technologies for lake restoration. *J. Limnol.* **2003**, *62*, 73–90. [\[CrossRef\]](#)
20. Waybright, T.J.; Terlizzi, D.E.; Ferrier, M.D. Chemical characterization of the aqueous algal fraction of barley straw (*Hordeum vulgare*) inhibiting *Microcystis aeruginosa*. *J. Appl. Phycol.* **2009**, *21*, 333–340. [\[CrossRef\]](#)
21. Varjo, E.; Liikanen, A.; Salonen, V.-P.; Martikainen, P.-J. A new gypsum-based technique to reduce methane and phosphorus release from sediments of eutrophied lakes. *Water Res.* **2003**, *37*, 1–10. [\[CrossRef\]](#)
22. Dittrich, M.; Dittrich, T.; Sieber, I.; Koschel, R. A balance analysis of phosphorus elimination by artificial calcite precipitation in a stratified hardwater lake. *Water Res.* **1997**, *31*, 237–248. [\[CrossRef\]](#)
23. Kajak, Z. *Eutrophication of Lakes*; PWN: Warsaw, Poland, 2001; ISBN 83-01-00470-3. (In Polish)
24. Kajak, Z. The effectiveness of different methods of lake restoration in order to improve the purity of their waters. *Ecological News* **1981**. (In Polish)
25. Dunalska, J. *Lake Restoration—Theory and Practice*; PAN, Monographs of the Environmental Engineering Committee: Warszawa, Poland, 2019; Volume 148. (In Polish)
26. Ząbek, E. Response of cyanobacteria to the fountain-based water aeration system in Jeziorak Mały urban lake. *Limnol. Rev.* **2014**, *14*, 51–60. [\[CrossRef\]](#)
27. Nordin, R.N.; McKean, C.J.P. *A Review of Lake Aeration as Technique for Water Quality Improvement*; B.C. Ministry of Environment: Victoria, BC, Canada, 1982.
28. Konieczny, R. Pulverization Aeration in the Conditions of Lake Barlineckie. Instytut Melioracji i Użytków Zielonych w Falenty; Raszyn, Poland, 2004. (In Polish)
29. Podsiadłowski, S. The use of wind energy in the restoration of lakes. *Clean Energy* **2002**, *4*, 14–15. (In Polish)
30. Dwivedi, P.; Sudhakar, K.; Soni, A.; Solomin, E.; Kirpichnikova, I. Advanced cooling techniques of P.V. modules: A state of art. *Case Stud. Therm. Eng.* **2020**, *21*, 100674. [\[CrossRef\]](#)
31. Ali Yildirim, M.; Cebula, A.; Sułowicz, M. A cooling design for photovoltaic panels—Water-based PV/T system. *Energy* **2022**, *256*, 124654. [\[CrossRef\]](#)
32. Sornek, K.; Goryl, W.; Figaj, R.; Dąbrowska, G.; Brezdeń, J. Development and Tests of the Water Cooling System Dedicated to Photovoltaic Panels. *Energies* **2022**, *15*, 5884. [\[CrossRef\]](#)
33. Konieczny, R. Monitoring of Operating Parameters of the Pulverizing Water Aerator System. Ph.D. Thesis, Institute of Technology and Life Sciences, Raszyn, Poland, 2013. (In Polish).
34. Laasri, S.; El Hafidi, E.; Mortadi, A.; Chahid, E.G. Solar-powered single-stage distillation and complex conductivity analysis for sustainable domestic wastewater treatment. *Environ. Sci. Pollut. Res.* **2024**, *31*, 29321–29333. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.