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Article

Renewable Energy Sources as Backup for a Water Treatment Plant

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Abstract: The article is focused on the issue of blackouts in a water industry and the selection of a renewable energy source for a water treatment plant. In the case of power outage, it is necessary to constantly ensure the supply of a drinking water, if this requirement would not be met, it could cause of deterioration of hygiene and health of the population. To be able to convey drinking water during a blackout, it is mandatory to have a backup power supply. The state of the current water treatment plants in the Czech Republic is that they are using diesel generators as backup power supply, which causes air pollution. There are other options of power supply that can be used, such as renewable energy sources. By using a multi-criteria analysis method, renewable energy sources were analyzed for a water treatment plant in the selected region. Based on the results, it seems that the most suitable choice is a small hydro power plant at the entry points of water treatment plant. Other possibilities of renewable energy sources that may be suitable for a water treatment plant and the usage of a multi-criteria analysis method for a water treatment plant in other countries are also discussed.

Keywords: water treatment plant; blackout; backup power supply; renewable sources; multi-criteria analysis method; weighted sum approach

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1. Introduction

A water supply is one of the most important services that ensures the efficient functioning of the community. Water is a non-substitutable foodstuff and guarantees minimum standards of hygiene; as such, it is an indispensable resource for meeting basic human needs. Water supply systems are an infrastructure designed to collect, treat, and supply water to people and industries. These systems have their own specifics, because they are complicated technical structures in which individual objects play different roles. What is more, water supply systems belong to the so-called "critical infrastructure", which are so essential that their continued operation is required to ensure the security of a given nation, its economy, and the public's health and/or safety [1]. Critical infrastructure protection includes all activities aimed at ensuring their functionality, operational continuity, integrity and prevention of threats, risks, or vulnerabilities. It is also important to ensure the resilience of the system by the ability to inactivate the effects of adverse events, as well as the ability to react quickly in the event of failures, attacks, and other events that disrupt its proper functioning. The water supply sector must be aware of the risk of energy failure and its social and economic consequences [2]. An overview of the technical elements in water supply and their dependence on electricity is shown in Figure 1 [3].

Energy blackouts, defined as the complete breakdown of the electricity supply causing a cascade of failures within the critical infrastructure for a longer period of time, are complex and unpredictably caused by a cascade of events [4]. Blackouts negatively affect a large amount of people lives, but also the course of the whole state and especially the economic development of the affected area [5].

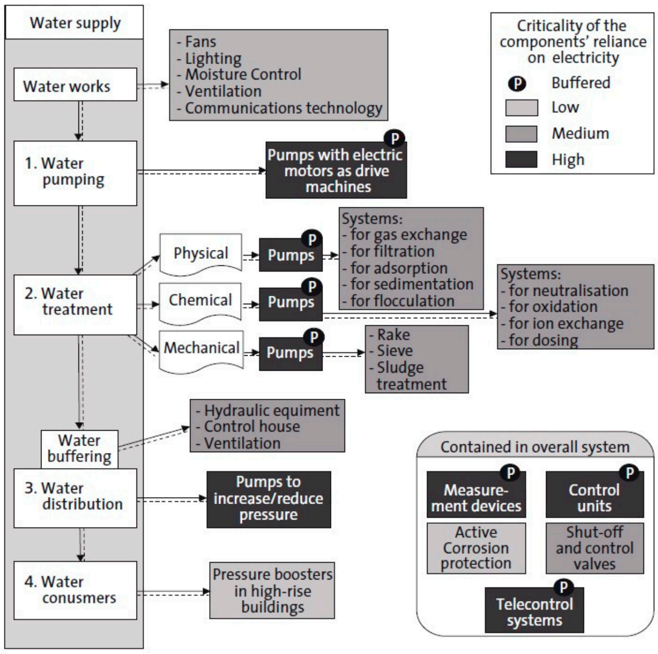

Figure 1. Technical elements in the water supply and their dependence on electricity [3].

An example occurred in August 2003, when Switzerland, whose electrical system is connected to that of Italy and France, faced a short circuit in one of its grids. A second grid replaced the demand of the first one. At the same time, there was a heat wave in Northern Italy, which required a considerable amount of electricity for cooling. The second Swiss grid was not able to provide the high demand for the time it took to repair the short circuit, by which time it also shut down. Within a short period of time, a domino effect happened causing the whole electrical system in Italy, beside the island Sardinia, to shut down, leaving over 55 million people without power for many hours [4]. Another excessive blackout took place in Auckland in 1998, which lasted five weeks and was caused by repeated malfunctions on high voltage cables [6].

Water outages caused by blackouts do not occur very often; hence, experiences with that kind of water outages are limited but can be suffered from other events such as the earthquake in Nepal in 2015 or the flooding in the Philippines in 2014. Therefore, the power outage is not likely to be the cause of the water outage. Natural disasters are a considerably larger threat for causing water outages [4]. The volume of water in water reservoirs lasts 24 h in the case of a power outage. A backup power supply must be installed; otherwise, the supply of drinking water to a water supply network is shutdown, with some exceptions. Political, legal, economic, social, technological and environmental decisions can influence the effects of blackouts, which can later play a considerable role in affecting water providers and customers [4].

The blackout and water outage can be split into three categories according to their cause: environmental, social and technical. The water sector can be affected directly or indirectly and the possible causes that affect it are show in Figure 2. Indirect effects on the water system caused by blackouts are described in detail. Power and water outages can disrupt daily life as a consequence of their effects [4].

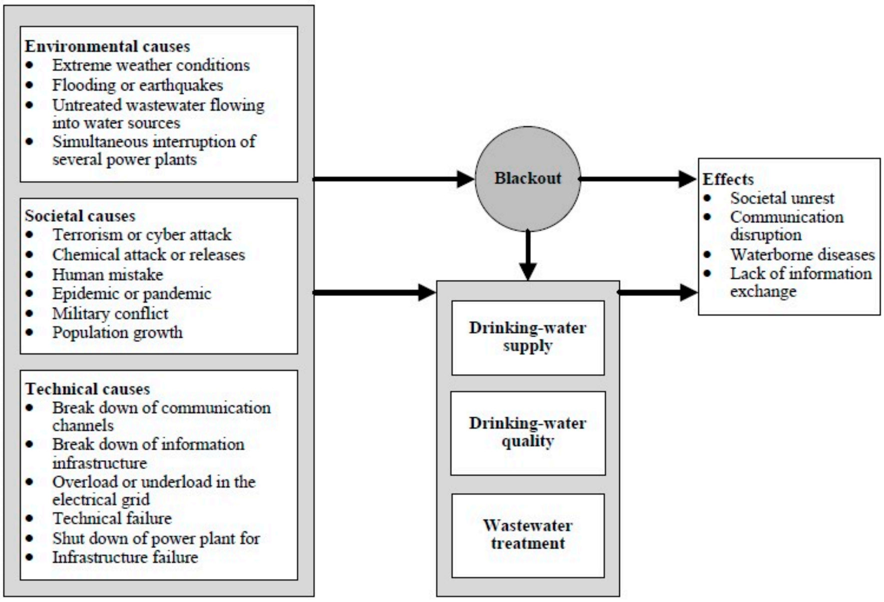

Figure 2. Diagram of the possible causes, hazard and effects [4].

In recent years, fossil fuel resources have decreased considerably around the world. For example, a study was conducted in India that shows that oil reserves will last for 22 years. Thus, it is necessary to look for alternative energy sources [7–9], because every water treatment plant is equipped with backup power, which typically uses diesel. As is known, this causes a couple of major challenges, such as emissions, which leads to environment pollution and finite sources of fossil fuels; thus, the price increases in the long term [10,11]. To solve these challenges, a new policy was introduced in recent years based on the use of hybrid energy systems with renewable energy sources to supply power to customers. A similar concept can be used for water treatment plants by using renewables as a backup power supply [12–16].

The change towards renewable energy sources is technically feasible and economically viable [17]. Technologies needed for renewable energy storage system's operation, generation and storage are available worldwide. Furthermore, the cost of renewable energy solutions continues to drop due to technical development [18].

Various studies were also carried out to find out if renewable energy sources are sufficient to satisfy power demand in all regions in the world and results were more than positive [19]. Thus, renewables can easily serve as backup power supply for water treatment plant. Other studies show that renewable energy sources can provide enough energy to satisfy the annual energy demand of the integrated energy system on a global scale [20,21]. Thus, it seems that use of renewable energy sources as a back-up power supply is reasonable from environmental and economical perspectives [22,23].

However, the transition to renewable energy sources will be for some countries, where there are severe climatic conditions, such as a high variation of seasons and high daily and yearly temperature differences [24]. Thus, photovoltaic systems can be integrated with battery storage to compensate the energy demand [25,26]. Wind generation may also use battery storage in the case of a lack of adequate winds and there are also some other alternatives for energy storage, such as hydrogen [27]. Hybrid systems can provide a stable power supply in rough conditions by merging photovoltaic, wind generation and battery storage [28,29]. Fuel cells can also be considered if wind generation and photovoltaic are not able to supply a sufficient amount of energy and when green hydrogen is used fuel cells provides emission free energy [30].

However, not all are suitable for specific water treatment plants. For that reason, a method for choosing the right renewable energy source needs to be developed.

We show, through one of the largest water companies in the Czech Republic, how this method is prepared to provide emergency water supply in the event of blackouts.

During the preparations of a "blackout power supply plan", it was necessary to ensure the assessment of operating facilities, inventory of mobile and stationary power plants and provide fuel, including storage design and any additional supplies.

The assessment of operating facilities enabled their division in terms of their importance for priority of securing electricity supply. In this way, the order for localities and installations with stationary or mobile generators was determined.

The company in question provides drinking water for more than 730,000 consumers and owns twelve water treatment plants, thirty wastewater treatment plants and thirty-five water industry objects, which includes many power plants. They also supply electricity to individual water industry objects, wastewater treatment plants and water treatment plants. Table 1 shows the sum of the real power of two water treatment plants, eight wastewater treatment plants and two water industry objects based on the power plant type.

Table 1. Summary of power plants.

Type of Power Plant	Summary of Rated Power (kW)
Small hydro power plant	944
Cogeneration unit	1459

Power consumption can be divided according to technologies, which are placed in water treatment plants. This division can be seen in Figure 3. It is obvious that pumping water has the largest share in power consumption. Other technologies contribute to power consumption, such as heating, conveyors, mixers, blowers, filtration, automatic pressure station and other technologies.

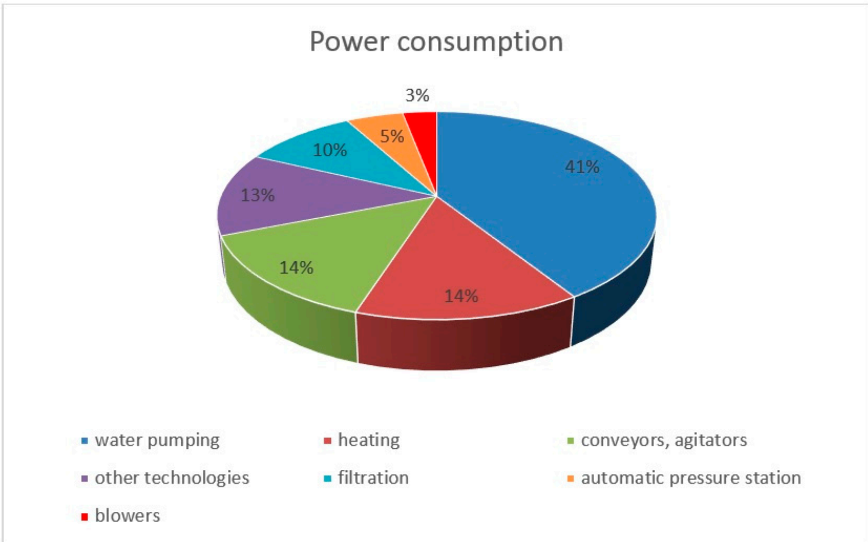

Figure 3. Water treatment plant's power consumption.

In the case of a blackout, a diesel generator is used, which generates electrical energy for the water treatment plant. The device is designed to not be able to return electricity back to the grid. This is accomplished by electromechanical interlocks of switching contactors and in the case of switching to direct operation from the grid (it all happens in the automatic mode).

The largest water treatment plants are equipped with stationary diesel generators of required power with an automatic start. Other water treatment plants are equipped with stationary power generators or are ready to use mobile power generators. Diesel generators are assigned (according to the power parameters) to specific operating facilities. Operational tests are carried out at regular intervals on those diesel generators, and their service tanks are maintained at full capacity.

Power generators need fuel to keep producing electrical energy. The region covers the first 24 h of a blackout with its own fuel reserves. It is necessary to be able to refuel with fuel from other sources for further operation of diesel generators and mobile power plants, and additional costs are paid by operator. The company bought a mobile fuel station to minimize the consequences of blackout when the distribution of fuel is crucial. This is a unique procedure in the Czech Republic. Thus, the company secured direct access to fuel in the event of a blackout, but the fuel station is used for the normal operation of all technological means within the company. A fixed (non-exceedable) supply is set at the fuel station, i.e., the volume that must be maintained in the event of a blackout. For this purpose, portable packaging was also purchased for the distribution of diesel in sufficient quantities.

2. Materials and Methods

2.1. Power Plant–Risks

Power plants have many advantages: they are mobile, can be operated immediately, the purchasing cost is not high and their operation is easy.

However, there are also negative aspects related to the combustion process, which is the principle of electricity production. Carbon dioxide (CO_2) and water (H_2O) are products of the pure oxidation of carbon and hydrogen when fuel is combusted. If impure oxidation happens, the products of combustion are carbon monoxide (CO) and hydrogen (H_2). When combusting hydrocarbon fuel using oxygen as an oxidant, nitrogen (N_2) is the largest component of flue gas. Another part of the exhaust gases is oxygen (O_2), which is not used for the oxidation of fuel, because there is a surplus. At high combustion chamber temperatures, nitrogen oxides (NOx) are formed by the oxidation of nitrogen from the air. The main part of those oxides is nitrous oxide (NO) and, in smaller amounts, there is nitrogen dioxide (NO_2). Under unfavorable oxidation conditions, unburned hydrocarbons of various compositions are formed. Unburned hydrocarbons appear in the exhaust gases due to the purge of the cylinder contents, which is caused by the external formation of the fuel mixture. If the fuel mixture is insufficiently sprayed, no air will reach the center of the fuel droplet, thereby subsequently forming solid carbon (soot) as a result of the decomposition of hydrogen molecules. Among other things, solid particles appear in the exhaust gases, which include dust, oil, ash and rust particles. The hydrocarbon fuel also contains a small amount of sulfur, which upon oxidation form sulfur oxides [31].

The energy carriers in the fuel are carbon, hydrogen and sulfur. If the pure oxidation of the fuel happens, the products are carbon dioxide, water and sulfur dioxide (SO_2). Carbon monoxide and hydrogen are created when impure oxidation occurs. The combustion of 1 kg of carbon produces about 3.7 kg of CO_2 [32].

Nowadays, the most discussed greenhouse gas is carbon dioxide. This greenhouse gas causes the creation of a radiation barrier, which limits the diffusion of the Earth′s heat in the environment. The consequence is global warming, which causing climate change [33].

Table 2 shows the specific emissions of CO_2 produced during the combustion of fuels. The values of specific emissions are rough estimates, especially for coal, because they depend on the composition of fuel, and this is usually very different for coal.

Table 2. Emission CO_2 from the combustion of selected fuels [34].

Fuel	**Emission CO_2**
	kg CO_2/kWh
Diesel	0.27
Petrol	0.26
Natural gas	0.21

As an example of the amount of CO_2 produced during a blackout for 24 h, a water treatment plant in the Netherlands was used. The water treatment plant is 70% to 96% self-sufficient, thanks to its renewable sources of electricity. The average power consumption is 69 kWh [35]. After recalculation using the value for diesel from Table 2, the value of CO_2 is 447.12 kg. This value is rough estimate, because power consumption is lower during power outages (only the devices necessary for the supply of drinking water are in operation).

Even within 24 h, the amount of CO_2 is vast. Therefore, it is appropriate to replace a commonly used diesel generator with sources of electricity, which do not produce greenhouse gases, thus they do not pollute the environment. Possible proposals are further discussed in the following section.

2.2. Possible Use of Renewable Electricity Sources during Blackouts

Renewable energy is a strongly discussed topic at present and it has gained a vast interest among experts and the general public. Hence, studies have increased in recent years on this topic in relative terms [36]. Fossil fuel depletion and global warming are issues that should be resolved, and renewable energy sources should have a considerable role in their resolution [37]. The main sources of energy today are fossil fuels, nuclear resources and renewable sources. Renewable sources contribute, in the smallest amount, to the rest of energy sources. Among the renewable sources, there are solar, wind, biomass, geothermal and hydropower.

Clean energy resources are incredibly needed because they are environmentally friendly. As awareness of a clean environment grows, it is believed that use of fossil fuels causes carbon dioxide emissions, environmental pollution and greenhouse gas problems [38].

The supply of sustainable energy also has issues and they influence parts of society and every opportunity to contribute must be recognized and correctly executed. E.g., the water industry in the UK consumes about three percent of its total energy and it has the opportunity to increase renewable energy generation [39].

All these electricity sources would have to be placed next to a water treatment plant to draw electricity from it in the case of a blackout. They would have to be able to connect to the off-grid mode, i.e., disconnect from the surrounding electrical distribution network. Then, they could start independently, regardless of the state of the surrounding network.

2.2.1. Small Hydro Power Plant

One of the options of how to supply a water treatment plant with electricity during a blackout is to use a small hydro power plant (SHPP). When a water treatment plant operates in the normal state, the SHPP generates electrical energy to be self-sufficient and possibly allows surplus energy to be sold in the public power grid. In the case of a blackout, a safety contactor automatically disconnects the water treatment plant from the electrical grid and starts charging batteries, which provides power only for devices accountable for conveying drinking water. The amount of batteries must be calculated according to the average power consumption in 24 h. If the SHPP has power output vast enough to be self-sustained, in the case of blackout, there is no change in operation, because the water treatment plant is already off-grid.

Water treatment plants consist of many control and regulation elements. It is mandatory to control the pressure or, if needed, the flow rate to reduce the hydrostatic pressure in the pipeline within the required limits. The control valves can be replaced by the SHPP to represent their function (Figure 4) [40].

A suitable placement for the SHPP is at the entry points into the water treatment plant and water cisterns and using the hydroelectric potential of the conveyed water, both treated and untreated.

A simple machine set of the SHPP contains an asynchronous generator and an adjusted water pump operating in a turbine regime. Such a technical solution allows the accurate regulation of pressure in aconsumption place with servo-valve, which handles changing flow parameters. More machine sets may be placed working parallelly (Figure 5) [40].

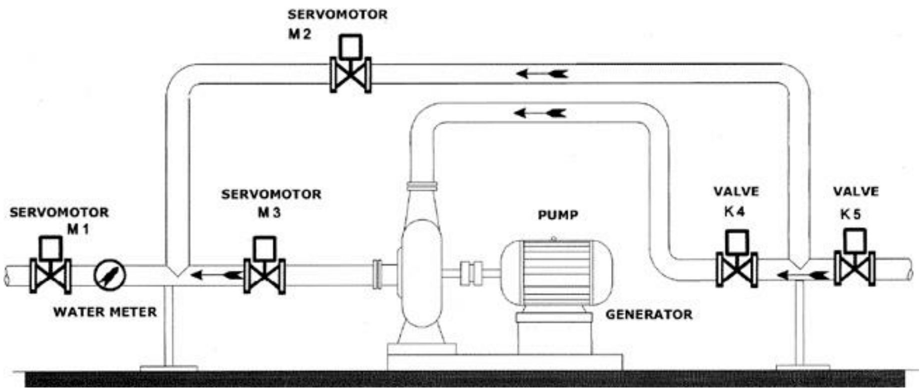

Figure 4. SHPP machine set [40].

Preserving the sanitariness of water is vital, which is why the systems for fitting of bearings and turbine regulation must be 100% secure to be able to ensure the sanitariness of water. Hence, it will remain classified as drinking water. The water treatment process is optimized with the help of SHPP, which aerates water and additives are mixed well in the treated water [40].

Figure 5. SHPP on a duct feeding untreated water into the water treatment plant [40].

Some of the Czech waterworks have taken a significant opportunity—using the energy of water conveyed in ducts. Waterworks produce and supply drinking water—great water volumes are conveyed in water ducts under pressure—and this can be used for electricity production. They have started building SHPPs at the entry points into the water treatment plants and water cisterns and using the hydroelectric potential of the conveyed water, both drinking and untreated. There is another important advantage—the possible holding of water, which means the partial regulation of electricity supply.

Examples of water treatment plants using a SHPP in the Czech Republic are described below:

- SHPP is placed in the inflow pipe of the distribution chamber and consists of a one turbine and three pump set. Parallel operation is not possible. Individual power outputs of this SHPP are 90, 110 and 130 kW;
- SHPP is situated in inflow pipe of feeder for untreated water. The machine set includes a double chamber turbine. The output power is 348 kW;

- SHPP is installed in the inflow pipe of the distribution chamber. Two turbines. Parallel operation is enabled. Power output 200 kW for each turbine;
- SHPP is placed in the inflow pipe of the water reservoir. One turbine. Power output is 37 kW.

2.2.2. Wind Power

Wind can make up a significant proportion of the renewable energy in a water treatment plant. It is a well-developed technology backed up by a better knowledge of wind resource availability and predictability.

Building a wind turbine on a water treatment plant's property can be difficult, because not every water treatment plant has a free space for a wind turbine. It is worth mentioning that wind turbines differ in size and power output, so it is possible to find a suitable wind turbine based on the parameters of a given property.

A chosen wind turbine does not have to have enough power to self-sustain the water treatment plant; if that is the case, the wind turbine will charge batteries, which supply power to the water treatment plant in the case of a blackout. When they are fully charged, the generated energy can be sold in the public power grid or can supply a part of the water treatment plant. The right amount of batteries has to be calculated in the same way as for the SHPP.

If the power output from a wind turbine is vast enough to provide power for the whole water treatment plant, the operation is still the same even when a blackout occurs, because the power is not coming from the power grid.

The site-specific potential for wind energy depends on the wind speeds at the location of the water treatment plant. For example, Figure 6 illustrates the measured average wind speed in the Czech Republic. Locations with average annual wind speeds of more than 5.6 m/s are suitable for wind turbines [41].

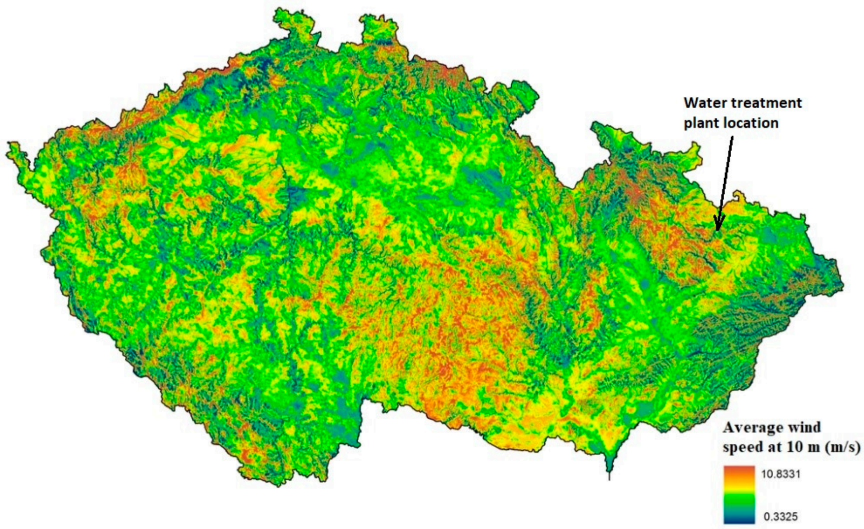

Figure 6. Average wind speed at 10 m.

Wind speeds are higher during the winter months, so the average hourly winter power output of the wind turbine is greater than the average summer power output. There is also a power output difference between daytime and night-time. On a full year basis, the average power output during the day is about 39.4% higher than during the night [35].

The most commonly used type of wind turbine is a horizontal axis turbine with a three-blade rotor spinning in a vertical plane attached to a nacelle. The Vestas V90 (2 MW) wind turbine is designed for low to medium speeds [35].

There is also scope of a smaller scale of vertical axis turbines as these technologies mature and become more efficient and reliable. The following examples exist in the UK (Howe 2009):

1. A 1.3 MW turbine at Hull Water Treatment Works;
2. A 1.3 MW turbine at Loftsome Bridge Water Treatment Works.

Another example is a water treatment plant that uses two windmills plus photovoltaic power. The windmills have wingspans 4 m, the horizontal axis elevated at 15 m and a power output of 3 kW each [42].

This source is not yet used for the needs of power supply of water treatment plants in the Czech Republic. Wind power plants have to be built close to water treatment plants and be connected with the possibility of being switched to the off-grid mode. However, it could be possible, because some water treatment plants are located in mountains or localities without civic development.

2.2.3. Photovoltaic Power

Photovoltaic energy production is nowadays one of the hottest topics in the water industry as this green energy source is becoming more and more workable in countries with high values of irradiance. In water treatment plants, they distribute energy consumption in pumps throughout the day, and it is not possible to supply electromechanical devices without energy storages, such as batteries [43].

The roof of water treatment plants is, in most cases, unused and it is good place to install photovoltaic panels. If the property of the water treatment plant has unutilized land, it is an appropriate place for installation too.

Electricity produced by photovoltaic panels heavily depends on the specific characteristics of the photovoltaic cells. These include conversion efficiency, the placement of photovoltaic panels in relation to the sun and de-rating factors, which cause the photovoltaic cells to work below the rated efficiency.

Conversion efficiency ranges from 12% to 16%, which differs depending on the manufacturer and cell type. The temperature coefficient of power indicates how strongly photovoltaic cells′ power output depends on the cell temperature, meaning the surface temperature of the photovoltaic array that is influenced by ambient temperature [35].

To maximize electricity production, the default tilted angle should be equal to the location′s latitude plus 15° in winter or minus 15° in summer [35]. The ground reflectance is positively influencing power output; for example, snow-covered areas may have a reflectance as high as 70% and grass-covered areas have a normal ground reflectance of 20% [44].

Photovoltaic technology produces DC electricity, so inverters are needed to convert DC power to AC power in order to be used by the water treatment plant.

The same operation principle during a normal state and a blackout can be used as for wind power.

Examples of photovoltaic used in water treatment plant are below [42]:

- Ireland's Group Water Scheme uses photovoltaic cells to directly power a water treatment plant and the site will be able to reduce energy costs by 70%;
- A water treatment plant in Puerto Real uses 20 photovoltaic modules of 210 W each plus two windmills of 3 kW each.

2.2.4. Fuel Cells

A fuel cell is considered as a clean power plant and it has a high efficiency. It can be labelled as renewable energy source when green hydrogen is used for electricity production. Green hydrogen is produced by using clean energy from renewable energy sources, such as solar or wind power, to split water by electrolysis. The chemical energy contained in fuels and oxidants is converted into electricity. Limitations by the Kono cycle neglect its energy and the energy conversion rate can reach 90%, which is two or three times better than for internal combustion engines. It has zero emissions; therefore, it does not pollute the environment and it is a clean and highly efficient power generating technology of the 21st century. Due to its many benefits (high energy conversion efficiency, zero pollution, low noise, no vibration and high reliability), domestic and foreign companies are focusing on fuel cells [45].

To achieve energy conservation and environmental protection, it is vital to increase the development of and market for fuel cells. Fuel cells are also known for their practicality worldwide. Since fuel cells are in their infancy, there are still some issues that should be resolved, e.g., electrode materials, manufacturing cost and catalysts. Hydrogen fuel cells are the best known and widely used around the world. Reductions in cost thorough development of hydrogen technology will have a positive impact on fuel cells and their problems will be solved [46].

One applicable example can be found in water treatment plants in India. A domestic company owns telecommunication towers across the whole country and experiences regular power outages. A company from the UK came up with a solution that included hydrogen fuel cells. After installation, there were no issues with power outages and fuel cells replaced diesel generators [47].

Electricity generated from fuel cells has also been used in another project, in which it was used to treat water with no moving parts and, using an adaptive software, system maintenance as straightforward [47].

This electricity source is not commonly used in the Czech Republic. It was included in the proposals so they can be complete. However, it is a topic for the distant future.

2.3. Selection of Renewable Electricity Source Using Multi-Criteria Analysis (MCA)

As was mentioned earlier, it is possible to use more types of renewable energy sources. However, some of them are not suitable for water treatment plants. When assessing suitable renewable energy sources, it is necessary to consider multiple criteria, which affect the properties of renewable energy sources, for example, the location of the water treatment plant. Each location has different wind speeds or solar radiation, which may not be sufficient for the realization of a wind power plant or photovoltaic.

A very important criterion is the lifetime of the renewable energy source, because a water treatment plant operates for several decades and it would not be efficient to change or repair the chosen renewable power source. Individual renewable sources use different technologies and that affects their design and structure. Therefore, they have various requirements for space. If photovoltaic is considered, the installation must be outside and enough space is needed either on roofs or land according to the power requirements. Wind power plants share similar requirements, but only small wind power plants can be installed on roofs. A SHPP has the advantage that its turbine is installed in pipes and the generator is typically placed next to the turbine. PEM fuel cells with hydrogen storage, on the other hand, must be installed in a separate room due to safety reasons.

A useful criterion is also the electricity cost, as the surplus of electricity from renewable energy sources is sold.

Many factors can greatly affect the decision of the suitable renewable energy source and this can lead to incorrect result. Furthermore, an objective decision that could be applied around the world could help many people to choose the most efficient solution for their requirements. For that reason, applying a multi-criteria analysis is the right approach because the chosen criteria can be adjusted and many different types of renewable power sources can be compared with each other.

Multi-criteria analysis (MCA) works by assessing the variants in accordance with several criteria. The "variant" is each solution of the chosen set, and the "criterion" is a variant characteristic to be analyzed. The first initial step of the MCA method is to set up the evaluation matrix (so-called criteria matrix) Y, whose elements reflect the properties of individual variants (alternatives) based on a certain set of criteria. The matrix Y consist of $i = 1, \ldots, p$ variants (rows of the matrix) and $j = 1, \ldots, k$ criteria (columns of the matrix).

The evaluation of the variants according to individual criteria creates elements of the matrix (y_{ij}). The evaluation of the matrix Y [48] is as follows:

$$Y = \begin{array}{c} \\ a_1 \\ a_2 \\ . \\ . \\ a_p \end{array} \begin{array}{c} \begin{array}{cccccc} f_1 & f_2 & \cdot & \cdot & f_k \end{array} \\ \begin{bmatrix} y_{11} & y_{12} & \cdot & \cdot & y_{1k} \\ y_{21} & y_{22} & \cdot & \cdot & y_{2k} \\ . & . & . & . & . \\ . & . & . & . & . \\ y_{p1} & y_{p2} & \cdot & \cdot & y_{pk} \end{bmatrix} \end{array} \quad (1)$$

The vast majority of MCA methods require cardinal information about relatively important criteria. It can be expressed using a vector of criteria weights:

$$\overline{v} = (v_1, v_2, \ldots, v_k) \quad (2)$$

$$\text{where } \sum_{j=1}^{k} v_j = 100\% \text{ and } v_j \geq 0$$

The higher the weight value of a given criterion, the more important it is.

2.4. Weighted Sum Approach (WSA) Method

Weighted sum approach (WSA) method is based on the principle of maximizing utility. However, a simplification is achieved so that it assumes only a linear utilization function. The procedure for this method is as follows. The normalized criterion matrix is created first $R = (r_{ij})$, whose elements are gathered from the criteria matrix $Y = (y_{ij})$ by using a transformation equation [48]:

$$r_{ij} = \frac{Y_{ij} - D_j}{H_j - D_j} \quad (3)$$

The matrix R represents the matrix of utility values from the i-th variant according to the j-th criteria. Based on the equation above, the criteria values are linearly transformed, so that $r \in \langle 0, 1 \rangle$, whereas D_j is the minimum criteria value in column j and H_j is the maximum criteria value in column j. This equation is used in the case that a criterion in a given column j is considered maximized. In the case of a minimization criterion, the normalization of such a column in the matrix can be performed directly using equation [48]:

$$r_{ij} = \frac{H_j - Y_{ij}}{H_j - D_j}. \quad (4)$$

When using the additive form of the multicriteria utility function, the utility of the variant ai is then equal to [48]:

$$u(a_i) = \sum_{j=1}^{k} v_j \cdot r_{ij} \quad (5)$$

The variant that reaches the maximum utility value is selected as the best, or it is possible to arrange the variant in descending order.

For individual renewable power sources, four criterions were selected, according to which the WSA method can be performed. Specific criterions such as lifetime, location, space requirement and electricity cost were chosen because the needed data can be gathered anywhere in the world; hence, the WSA method is not relevant only in the Czech Republic.

3. Results

The water treatment plant in question for the selection of the renewable energy source is located in the North Moravia region. It has a capacity of 2600 L/s and a head of 50 m and the average power consumption is 120,000 kWh. The wind speed where the water treatment plant is located is 4 m/s (see Figure 6). Figure 7 shows the solar radiation in the

Czech Republic and the location of the water treatment plant. Solar radiation for the water treatment plant, according to values in Figure 7, is 1050 kWh/m^3.

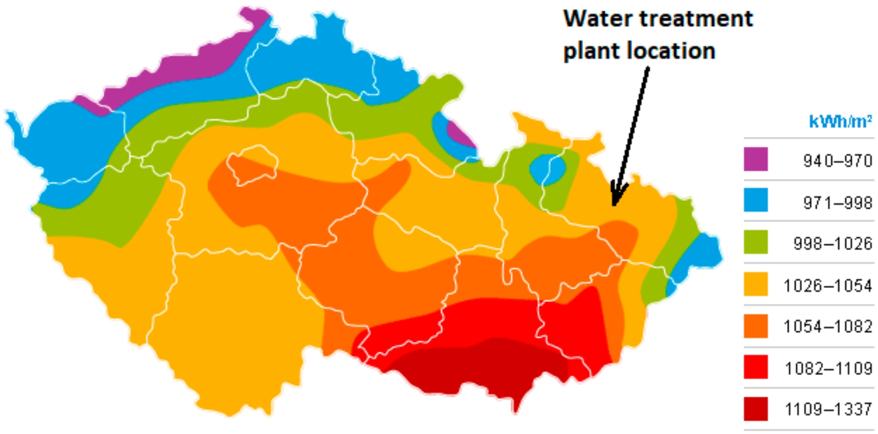

Figure 7. Solar radiation in the Czech Republic.

The useable roof area of the water treatment plant for photovoltaic installation is about 3300 m^2. Based on the average power consumption and the dimensions of photovoltaic panels (1955 × 995 mm^2), the needed area on the roof is 730 m^2. Thus, the photovoltaic power plant can be easily installed on the roof and to cover the power supply requirements. Note that the land around the power treatment plant is sporadically planted with trees and has no buildings; therefore, solar radiation is not blocked.

The free area on which the wind turbine could be built is about 4900 m^2. According to the power requirements, the water treatment plant would need a 50 kW wind turbine. The nominal power of the wind turbine is reached at 10 m/s. According to that, the 50 kW wind turbine will provide approximately 175,200 kWh, when the wind speed is 4 m/s. This specific wind turbine tower is 18 m tall and consist of three blades. The free area has dimensions 70 × 70 m, so we may conclude that this space is sufficient based on the dimension of the wind turbine tower.

The space required for the PEM fuel cells is quite small, for example, the FCWAVE module from Ballard has the following dimensions: 741 × 1209 × 2193 mm (length × width × height) and its rated power is 200 kW. Issue comes with hydrogen storage, because the fuel cell module needs about 4 g of hydrogen per second. Due to that, even for one day, 345 kg of hydrogen would be needed. The manufacturer Steelhead Composites offers a storage tank that can hold 384 kg of hydrogen and the dimensions are 6.1 × 2.4 × 2.9 m (length × width × height). Inside of the water treatment plant, there could be a fuel cell module and storage tank installed in a room where the diesel generator is placed. However, fuel cell module would be able to provide electricity only for one day.

When deciding what renewable energy source to use for a lifetime, the photovoltaic and wind power have to last 60, 30 and 20 years, respectively, as it is very important criterion and correspond to the individual values for SHPP [49]. The PEM fuel cell module's lifetime is up to 5 years and that value is usually determined by heavy duty PEM fuel cell modules used in maritime areas.

The cost of electricity for individual renewable energy sources was taken from Energy Regulatory Office in 2020, when the energy regulatory journal was published.

The values of the criteria, which were gathered from the evaluation of the data criteria, are shown in Table 3. When evaluating the lifetime criterion, it is evident which renewable power source will receive the most value and it is SHPP. However, PEM fuel cells will not run all the time and its lifetime was assessed from the hours of continuous operation. Therefore, the lifetime of the PEM fuel cells as a backup power supply will be much longer and, thus, the value is the same as that of wind power.

Table 3. Criteria data of the renewable power sources.

	Lifetime	Location	Space Requirement	Electricity Cost
SHPP	60 years	2600 L/S AND 50 M	Installation in existing pipes	2258 CZK/MWh
Photovoltaic	30 years	1050 kWh/m^2	730 m^2	1560 CZK/MWh
Wind power plant	20 years	4 m/s	900 m^2	1969 CZK/MWh
Hydrogen fuel cell	5 years	Power generation is not affected by location	45 m^2	-

From a weight perspective, the second criterion is location and the best evaluated renewable energy source are PEM fuel cells, because they are installed inside and their electricity production is not affected by external influences. In the location where the water treatment plant is built, there are no optimal conditions for a wind power plant, as there is a low average wind speed of 4 m/s. This is the lower limit of wind speed for electricity production. Therefore, the wind power plant obtained the worst values among all renewable energy sources. Photovoltaic received a slightly better evaluation because solar radiation has better average values for optimal electricity production. SHPP obtained the second best evaluation due to a sufficient flow and head to sustain the water treatment plant.

The third criterion, but also an important indicator of what renewable energy source is suitable, is space requirement. The turbine for the SHPP can be easily installed in the existing pipes and other equipment, such as the generator, can be installed alongside the pipes. An asynchronous generator or a hydro generator is usually used and the needed space for installation is quite small. The water treatment plant has free space that is large enough for the SHPP to be installed without the adjustment of construction; thus, the SHPP obtained the best values. The second best evaluation was that of the photovoltaic, because, on the roof of the water treatment plant, the needed number of photovoltaic modules can be installed, which would cover the power requirements of the water treatment plant. However, some adjustments of the roof and the construction for photovoltaic modules would be needed. The wind power plant and the hydrogen fuel cells require extensive adjustments, such as modifying land and surroundings or building additional room for the hydrogen fuel cells. The wind power plant obtained the same value as the photovoltaic because its faces the same problems as photovoltaic and it needs additional adjustment for placement in the power plant. More specifically, ground adjustments for the wind power plant foundation and cable routes would be needed. The PEM fuel cells did not obtain the maximum value, even though they can be placed with the hydrogen storage in the room where diesel generator is, since it can supply power just for one day and another hydrogen storage would not fit in the room.

The evaluation of individual renewable energy sources was also conducted according to the electricity cost obtained from the energy regulatory office. Fuel cells have limited amount of hydrogen in storage and that is why they are not capable of producing surplus electricity, which could be sold; thus, it received a value of zero.

The evaluation of data in Table 4 was carried out by using the weighted sum approach (WSA) method in the MCA8 program for the multi-criteria analysis. The program requires criteria weights (Figure 8) to be filled in to ensure that it will successfully run the evaluation. The results are shown in Figure 8 and it is evident that the best solution for the water treatment plant in the North Moravia region is SHPP. Interestingly, the wind power plant and hydrogen fuel cells have almost identical results.

Table 4. Criteria values of the renewable power sources.

	Lifetime	Location	Space Requirement	Electricity Cost
SHPP	5	4	5	5
Photovoltaic	4	3	4	3
Wind power plant	3	2	4	4
Hydrogen fuel cell	2	5	3	0

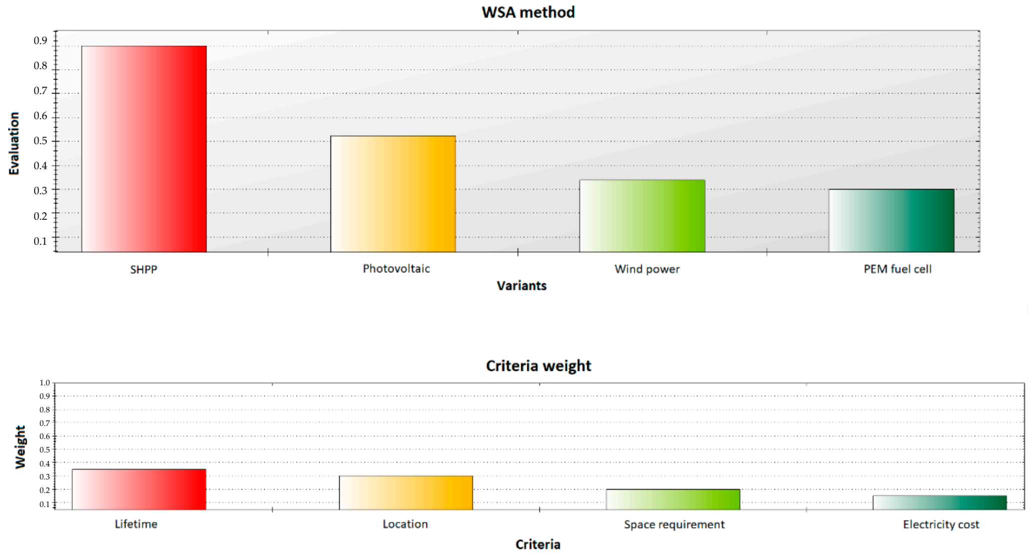

Figure 8. Results of the weighted sum approach method.

4. Discussion

The pollution of the environment is a widely discussed topic at present. It seems that replacing a backup power supply in water treatment plants is a little too much, but there are countless of plants around the world. Most of them use diesel generators, which combust diesel. Diesel contributes significantly to the pollution of the environment. Therefore, it is very important to replace current backup power supplies with renewable sources. Not all renewable sources are suitable as backup power supplies for water treatment plants. Table 5 describes the strengths and weaknesses of renewable sources, which were discussed in this article.

It is noticeable that SHPPs are, from the water treatment plant point of view, an appropriate solution. They can be used to supply power to an entire plant or serve as a backup power supply during blackouts. However, SHPPs have their limits and they are heavily dependent on water flow and head. Additionally, the best place of installation of SHPPs are in input pipes, which supply the water treatment plant with water and water flow is secured by gravity. Output pipes are not a great place to install SHPPs, because some water treatment plants use pumps to supply customers. Hence, in the case of a blackout, SHPPs would not generate electricity. In conclusion, SHPPs as a backup power supply should be placed in pipes, whose flow of water is not affected by blackouts. Wind turbines are very difficult to build, not from engineering point of view, but because of obtaining all the necessary permissions. The situation is worse near built-up areas, which is why wind turbines are not likely to be used often in the Czech Republic. Photovoltaic is suitable as a backup power supply, but its power output fluctuates. This can be solved by using an adequate battery capacity. Fuel cells are the most appropriate as a renewable source in many parts of industry, but at present, they are too expensive to be used as a backup power supply. Additionally, the infrastructure for hydrogen is at its infancy. The issues will be solved with the increasing commercialization of fuel cells.

Table 5. Strengths and weaknesses of the renewable power courses.

Type of Power Source	Strengths	Weaknesses
Small Hydro Power Plant	Proven technology. Reliable and robust. Relatively stable source of power in time. Process optimalization of untreated water.	Payback period is long if it is not supported.
Wind Power	Proven technology. Reliable and robust.	Complicated planning procedure. High potential for complaints from nearby residents. Availability of wind resource is dependent on geography.
Photovoltaic Power	Useful in remote locations. Proven technology. Reliable and robust.	Low energy density. Technology is still expensive per kWh, which provides long payback periods. Prone to vandalism in exposed areas.
Fuel Cells	Highly efficient. Reliable and robust. No vibration; low noise.	Expensive. Infrastructure for hydrogen is not finished.

5. Conclusions

The results of the WSA method are very clear (Figure 8) that SHPPs are the best renewable energy source for water treatment plants in the North Moravia region of the Czech Republic. However, there may be cases when other renewable energy sources are suitable for a water treatment plant in a given location, using WSA method. For example, photovoltaic in a location where solar radiation reaches values above 1600 kWh/m^2 would mean a larger electricity production and, after the battery storage being fully charged, the sale of surplus electricity. Therefore, the criteria value of location would have a greater value and this could lead to different results in the WSA evaluation.

A wind power plant could obtain better results and match SHPPs, if the water treatment plant was in a location where daylight in winter is only 5 h throughout a day (due to that, photovoltaic would not be suitable), for example, in Scandinavia. Additionally, in northern regions, wind speed is very high and, hence, electricity production is better.

As for PEM fuel cells, there is not much room for improvement of the criteria values. The location will have a maximum value in any given place, because PEM fuel cells are installed indoors. The last criteria value that can be affected is space requirement. It will have a maximum value when no building modifications are be necessary. In consideration of all criteria, hydrogen fuel cells will not be the best solution for some time.

As described above, the WSA method for the selection of suitable renewable energy sources can be applied even for water treatment plants in different countries than the Czech Republic. However, some adjustments of the criteria evaluation according the gathered data of the given water treatment plant will be necessary. For example, the price of the surplus electricity for sale is different in other countries. For that reason, criteria values will be slightly different than those for water treatment plants in the Czech Republic. As for the other criteria, such as space requirement and location, no additional adjustments would be needed, because the evaluation of the mentioned criteria is the same for other countries.

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