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Electricity supply to irrigation systems for crops away from urban areas

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Abstract: Water scarcity is a phenomenon that is occurring more and more frequently in larger areas of Europe. As a result of drought, there are significant drops in yields. As demand for food continues to rise, it is becoming necessary to bring about a substantial increase in crop production. The best solution to water scarcity appears to be irrigation for crops that are particularly sensitive to drought. Today, many technical solutions are used to supply and distribute water to crops. The optimal solution is drip irrigation, which makes it possible to deliver water directly to the plant root system to save melting freshwater resources. In the article special attention was paid to methods of supplying electricity to power irrigation pumps. The analysis was made for areas with a significant distance between the agricultural land and the urbanised area (which has water and electricity). The authors have selected the parameters of an off-grid photovoltaic mini-hydropower plant with energy storage (with a power of 1.36 kW). An analysis was made of the profitability of such an investment and a comparison with other types of power supply. Based on the performed calculations, a prototype power supply system equipped with photovoltaic panels was made to show the real performance of the proposed system. The tests carried out showed that the irrigation pump will be powered most of the time with a voltage whose parameters will be very close to the nominal ones.

Keywords: irrigation system, microgrid, power supply, solar photovoltaic (PV), solar water pumping system

INTRODUCTION

In recent years there has been an increasing precipitation deficit in Poland. It is mainly due to the very high weather conditions in the same periods of consecutive calendar years [RZEKANOWSKI *et al.* 2011; STEPNOWSKI 2020]. Precipitation and evaporation fluctuate. The precipitation extremes and their frequencies also fluctuate. The variability in climatic timescales of all water balance components is very large, in accordance with Hurst–Kolmogorov stochastic dynamics [KOUTSOYIANNIS 2020]. Water shortage in agriculture results from a decrease in precipitation and increased air temperature and insolation (evaporation phenomenon). Plant yields are also significantly affected – the higher the yield, the higher the water evaporation (transpiration).

Water scarcity in agriculture results in a significant deterioration of yields, both in quality and quantity. Lack of precipitation is associated with a lack of water supply to the soil, from where plants draw their nutrients. It affects both the growth of plants and their vitality [KOWALIK 2010]. Research results indicate that the occurrence of drought periods causes significant losses in cereal, fruit, and vegetable crops [ŻARSKI *et al.* 2013]. Depending on the duration of drought, these losses range from 20 to 80%, or in extreme cases even 100% of the crop [ŁABĘDZKI 2009].

The effects of drought can be counteracted by irrigating plants that are particularly sensitive to water shortages. A properly selected programme of water supply to plants ensures a proper rhythm of their growth and development. As a result, it leads to improved crop yield and quality [STACHOWSKI, MARKIEWICZ 2011]. Moreover, the introduction of crop irrigation can lead to an increase in the competitiveness of Polish agricultural holdings, mainly by reducing the dependence of production on climate change [KUCHAR, IWAŃSKI 2011]. Using precise irrigation techniques (based on advanced automation), especially in vegetable and fruit growing, allows for covering the actual demand of a given type of plant for water [KUŚMIEREK-TOMASZEWSKA *et al.* 2012]. Moreover, it ensures the economic management of water, which is becoming a scarce commodity in some regions of Poland and the world [JANKOWIAK, BIEŃKOWSKI 2011]. Currently, agriculture is perceived as inefficient in its use of water, and even minor improvements in irrigation efficiency can make a big difference to the water balances of an area [SCHEIERLING, TRÉGUER 2018]. Another way to achieve a trade-off between the amount of water supplied by irrigation and crop losses is to use deficit irrigation. This method has been described by many researchers [HASHEM *et al.* 2018; MUBARAK, HAMDAN 2018; WAKCHAURE *et al.* 2018; YANG *et al.* 2018] and consists in creating a deficit in the amount of water that will induce an acceptable (mainly from an economic point of view) yield loss. It reduces the cost of the irrigation system. The continuous increase in the number of cattle and pigs causes the need to manage animal waste, in particular liquid manure. Using them for the production of energy in biogas plants gives the possibility of obtaining energy, but also highly efficient natural fertiliser and water-saving [ROMANIUK *et al.* 2021; SKIBKO *et al.* 2021a; WAŁOWSKI 2021].

The most commonly used irrigation technology for surface crops is sprinkler irrigation using frontal or spool devices. However, this is connected with the high consumption of water resources. Therefore, especially for row crops, the profitability of water-saving drip lines, run both on the surface and under the soil surface, should be analysed [ŻARSKI *et al.* 2007]. In drip irrigation, water is applied directly to the root system of plants. The green part of the crop is not soaked, which reduces the risk of fungal diseases. The use of full automatics (combined with the measurement of soil temperature and humidity) allows the optimum, constant soil moisture to be obtained [KARCZMARCZYK, NOWAK 2006]. Drip irrigation limits the seepage of water into the soil and reduces evaporation. The maximum reduction of water evaporation is achieved by running drip lines under the top layer of soil so that water is supplied directly to the plant's root ball (this applies mainly to perennial plants). In addition, drip irrigation makes it possible to apply fertigation, i.e., small doses of fertilisers (primarily nitrogen and potassium) with water. Fertigation with complete macro-and micronutrient fertilisers is used very rarely. It is mainly used to restore depleted soils or on oligotrophic soils. Fertilisers given in this way are better utilised by the plant, resulting in increased yields [ZOTARELLI *et al.* 2009]. The essential components of a drip system are the emitters (drippers). They are equipped with pressure compensation so that the first and last drippers deliver the same amount of water to the plant. Drip heads are available as single emitters (in low-temperature crops) or as strips and drip lines (in field crops). Labyrinth drippers allow for a turbulent water flow so that the water is self-cleaning, reducing the risk of clogging.

The use of irrigation is unfortunately not possible in every agricultural area. It is connected with the necessity of supplying water under high pressure. It is most often achieved by providing water through pipelines from urbanised areas. The use of water from deep wells or reservoirs (natural or artificial for rainwater) for irrigation requires pumping. For this purpose, water pumps powered by electricity are used. Electricity sources are usually power generators or batteries with inverters. The use of battery power was associated with the constant need to charge the batteries. Therefore, it seems crucial to find alternative sources of energy. In this case, it is important to consider the impact of the power plant on the power grid [SKIBKO *et al.* 2021b]. The article analyses the possibility of using a photovoltaic installation to drive water pumps.

It is clear from the available research that hybrid power systems with RES sources can be reliable, economical, efficient [SCHNITZER *et al.* 2014]. Since electricity is not available in rural areas, diesel generators are widely used for irrigation. However, this is a costly solution and also results in the emission of greenhouse gases into the atmosphere. Solar irrigation systems have recently started to be used in Bangladesh, for example, due to the availability of solar radiation, easy installation, and the relatively low price of solar panels [KHAN 2012; MUHAMMAD *et al.* 2014]. However, solar pumping is not suitable for very high water demand (large land area) because the efficiency of a single unit is very low. The energy yield and therefore the amount of water pumped varies with changes in solar radiation. Therefore, an irrigation system powered only by a photovoltaic system is best suited for midday when solar exposure is maximum [SHINDE, WANDRE 2015]. As this is not the most efficient irrigation time in practice, it is very common practice for PV systems to be supported by fossil fuel (diesel, gas) generators [SHOEB, SHAFIULLAH 2018]. As part of the work carried out by the authors, further research was carried out to verify the possibility of using solar systems to power irrigation systems, in the most efficient way possible. These studies were carried out on a designed and manufactured prototype system. Particular attention was paid to the parameters of voltage generated in the photovoltaic system, used to power the water pump. Maintaining the appropriate parameters of the quality of electricity supplying the electric motors is a very important aspect affecting their life. When induction motors are supplied with the wrong voltage, the rotating magnetic field becomes elliptical instead of circular. As a result, the machine cannot produce full torque and there is more rapid wear of the machine bearings (due to uneven torque) [HOLDYNSKI, SKIBKO 2014].

MATERIALS AND METHODS

Some agricultural land is so far from urbanised areas that it is not economically viable to run pressurised water supply networks. The use of deep-well pumps (pumping water from deep wells) or surface/submersible pumps (pumping water from natural or artificial reservoirs) requires electricity to power them. The construction of electricity networks is usually accompanied by high costs (often, due to distances, electricity has to be transmitted via 15 kV lines) and administrative difficulties (the consent of the owners of the land through which the power line is to run is required). Therefore, the optimal solution seems to generate the necessary amount of electricity at the place of use. For this purpose, it is most convenient to use renewable energy sources. The technologically most straightforward and most economical would be to use wind- or solar-powered sources. Given the average wind speed in Poland during the spring and summer months (when irrigation is needed), wind turbines are inefficient. Given that water scarcity is often associated with many sunny days, the optimal solution is to build an off-grid photovoltaic power plant. Such a power plant is not connected to the electricity grid but only works on the island of the energy producer's equipment. Given the need to irrigate during limited sunlight (morning and/or evening), the power plant must be equipped with energy storage. As energy storage, mainly lithium-ion batteries are used, whose capacity is selected according to the power and operating time of the connected consumers. In irrigation systems, the largest consumer is the water pump, whose power varies between 0.5, and 30 kW (depending on the number and length of irrigation lines). Pumps with a capacity above 2 kW are usually made as 3-phase pumps.

In the analysis carried out for the supply of the irrigation system, the following pump data were assumed to supply the irrigation line:rated voltage U = 230 V, rated power P = 1.3 kW, power factor cos j = 0.7, frequency 50 Hz, maximum lift height 55 m, maximum suction depth 8 m, maximum pressure 0.55 MPa, maximum water output 6000 $dm^3 \cdot h^{-1}$. Power of auxiliary and control equipment and power losses in the system P_s = 0.2 kW. It was assumed that the irrigation system would use the total capacity of the pump for a time t = 4 hours per day. Therefore, the daily electricity demand (E_d) of the system calculated from the formula (1) is 6 kWh:

$$E_d = (P + P_s)t \tag{1}$$

For this demand, a battery bank must be selected to cover the system's daily electricity (AC – alternating current) sinusoidal voltage for the power supply, it must be connected to the batteries via a converter system. For this purpose, an AC/DC inverter dedicated to off-grid systems will be used (DC – direct current). The basic features that an inverter must have are:
– sinusoidal output voltage,
– met power quality parameters [Wiśniewski, Skibko 2017],
– automatic control of the battery charging process,
– an intelligent combination of energy sources – photovoltaic panels/battery bank.

In the case under consideration, an inverter with a nominal power of 3 kW has been selected, whose good continuous power is 1.5 kW at 230 V. The standard efficiency(η) of such a system is approximately η = 0.93. Therefore, the actual energy that must be generated in the battery bank (E_a) is calculated from the formula:

$$E_a = \frac{E_d}{\eta} \tag{2}$$

and must be a minimum 6.45 kWh. With this in mind, a lithium-ion battery system dedicated to photovoltaic systems with the useful energy of 6.8 kWh was selected to power the water pump. The lifetime of such batteries is typically around 5,000 complete discharge cycles, which, assuming the system operates 90 days per year, gives a possible lifetime of 55 years.

Photovoltaic panels of 340 W will be used to charge the designed battery. The energy generated in the panel will be supplied via an off-grid inverter both directly to the pump and will also be used to charge the batteries. Assuming an average day length of 10 h in summer and that the actual power produced by the panel will be on average (for the entire period analysed) half of the rated capacity, 4 panels are needed to produce 6.8 kWh of energy.

In addition to the panels, inverter, and battery bank, the photovoltaic installation should be equipped with the devices listed in Table 1 to transmit the generated energy and protect the system against overvoltages and overcurrents.

Table 1. List of equipment for the designed water pump supply system

Device	Quantity
AC/DC inverter dedicated for off-grid systems	1 pc.
Photovoltaic panels 340 W	4 pcs.
Lithium-ion battery with 6.8 kWh capacity	1 pc.
DC wiring	1 pc.
Fuse switch disconnector with fuse link	2 pcs.
DC surge arrester	2 pcs.
AC wiring	1 pc.
Overcurrent circuit breaker B10	1 pc.
Residual current circuit breaker, type A, 25/0.03A	1 pc.

Source: own elaboration.

The designed system makes it possible to supply water to an area with a daily demand of up to 24,000 $dm^3 \cdot day^{-1}$. It should be emphasised that the analysed set is dedicated to the area of 1–2 ha. In the case of larger areas, it would be necessary to duplicate such a system by increasing the power of a single source (central power supply) or to build several analogous sets (distributed power supply). From the economic point of view, a central power supply will be much more beneficial than a distributed one.

Based on the calculations, a prototype was made to show the real performance of the proposed system. The block diagram of the system analysed is shown in Figure 1. Tests showed that the system performed well on sunny and slightly cloudy days. If there were three consecutive days with full cloud cover, then there was not enough energy to charge the battery. However, there was also less need for water, as overcast days were usually accompanied by rain. In order to check the behaviour of the quality parameters of the generated voltage supplying the water pump, electrical measurements were carried out with the use of an electrical power quality analyser PQM 701. Based on the obtained current and voltage waveforms, statistical analysis was performed, showing the deviation of the basic parameters of voltage and current supplying the irrigation line. Number of samples analysed: 6099. The obtained data set was subjected to statistical analysis by means of the following indices:
– arithmetic mean

$$\bar{x} = \frac{1}{n}\sum_{i-1}^{n} x_i \tag{3}$$

– median

$$Me = \begin{cases} x_{(n+1)/2} & \text{for odd } n \\ \frac{1}{2}\left(x_{n/2} + x_{(n/2)/2}\right) & \text{for even } n \end{cases} \tag{4}$$

– standard deviation

$$SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{5}$$

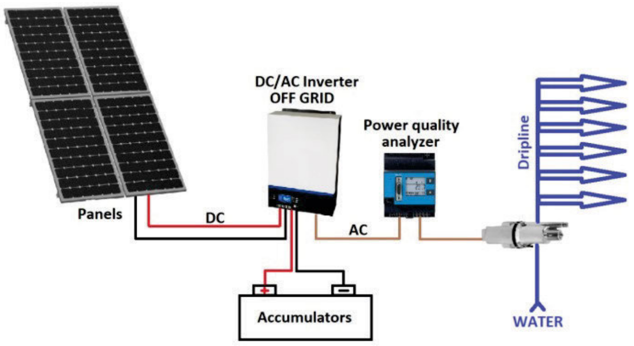

Fig. 1. Block diagram of the analysed system supplying the water pump of the irrigation system; AC = alternating current, DC = direct current; source: own elaboration.

– range

$$R = x_{\max} - x_{\min} \tag{6}$$

– coefficient of variation

$$V = \frac{s}{\bar{x}} 100\% \tag{7}$$

where: x_i = the individual values of the random variable, n = sample size, $x_{(n+1)/2}$ = the value of an element with number $(n+1)/2$ in a non-decreasingly ordered set of values of a random variable, $x_{\min}$ = the smallest value of a random variable, $x_{\max}$ = the largest value of a random variable.

RESULTS AND DISCUSSION

The following electrical power system parameters were analysed: voltage frequency (f), root mean square (*RMS*) voltage (U), *RMS* current (I), total harmonic distortion of voltage (THD_U), total harmonic distortion of current (THD_I), power factor ($\text{tg}(\varphi)$) [Hołdynski, Skibko 2014]. The obtained results of the statistical analysis are presented in Table 2 and Figure 2.

Tests carried out on the built prototype show that the irrigation pump will most of the time be powered by a voltage whose parameters will be very close to the rated voltage. The voltage frequency deviated only slightly from 50 Hz and its value was within the legal limit of ±10% of the rated voltage. The voltage value at the source decreased when the pump was switched on but did not fall below safe values from the point of view of pump operation. It is worth noting that the voltage and current distortion coefficients have small values, which indicates that the pump will not experience phenomena caused by higher harmonics.

Table 2. Results of statistical analyses of the supply voltage in the investigated system

Variable	Mean	Median	Standard deviation	Coefficient of variation
f	50.000	50.000	0.019	0.038
U	224.045	220.99	0.095	1.056
I	7.286	7.272	0.527	3.687
THD_U	0.996	0.990	0.141	14.186
THD_I	6.442	6.610	1.069	16.593
$tg(\varphi)$	0.452	0.450	0.015	–9.733

Explanations: f, U, I, THD_U, THD_I, $\text{tg}(\varphi)$ as in the text in p. 76.
Source: own study.

On light soils with the permeable substrate, drip irrigation is usually an indispensable crop-creating factor, contributing to increasing crop yields. In medium soils with cohesive soils, drip irrigation usually plays a supplementary role in temporary water shortages. Nevertheless, also there it contributes to increasing and stabilising yields in particular years. The yield increase induced by irrigation, depending on the crop, averages 35 to over 50% per year [Żarski *et al.* 2013].

To determine the profitability of investment in irrigation powered by a photovoltaic installation, first of all, the costs of construction of the said power supply installation should be selected. Calculations show that to power the pump, one should choose an off-grid photovoltaic set adapted to supply 230 V *AC* receivers, whose power does not exceed 1500 W, with a daily demand for energy of about 6.8 kWh. The estimated cost of such a set is approximately 15,000 PLN net. Additionally, the price of the pump (about 700 PLN) and the price of irrigation lines (about 400 PLN·km^{-1}) should be added (USD1 ~ 4 PLN in 2021). The cost of the line will strictly depend on its total length and the number of drippers.

Assuming that the irrigation system will supply water to a cornfield of 1 ha, considering an increase in yield according to data available in the literature, the yield will be higher by about 3.5 Mg. Assuming an average price of maize for grain equals 900 PLN·Mg^{-1}, this gives an average annual profit of 3,150 PLN. Therefore, the purchase of the photovoltaic installation to power the irrigation pump will pay for itself in nearly 5 years – assuming an expenditure of PLN 1,000 for inspection and modernisation of the installation once every 5 years (according to Polish regulations). Assuming the installation's lifetime at the level of 25 years, the investment in the photovoltaic energy source will bring a total profit of approximately 25,000 PLN. Figure 3 shows the value of the investment in each year of its life (surplus of the net present value of the investment over the initial expenditures). The net present value (*NPV*) is the difference between the discounted cash flows and the initial outlay and is calculated from the relationship:

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - I_o \tag{8}$$

where: CF_t = net cash flow over time, r = discount rate, I_o = investment outlay, t = consecutive periods of investment (month, quarter, year, etc.)

The above analysis is only correct when using existing, ready-made drip irrigation systems installed in the field. Otherwise, the cost of drilling a well (in the absence of a natural reservoir) and the cost of making irrigation lines should be added to the cost of the photovoltaic installation.

As the power source for the irrigation pump itself has been analysed, it is helpful to compare the cost of building it with other energy sources. In fact, in areas remote from urban areas, there

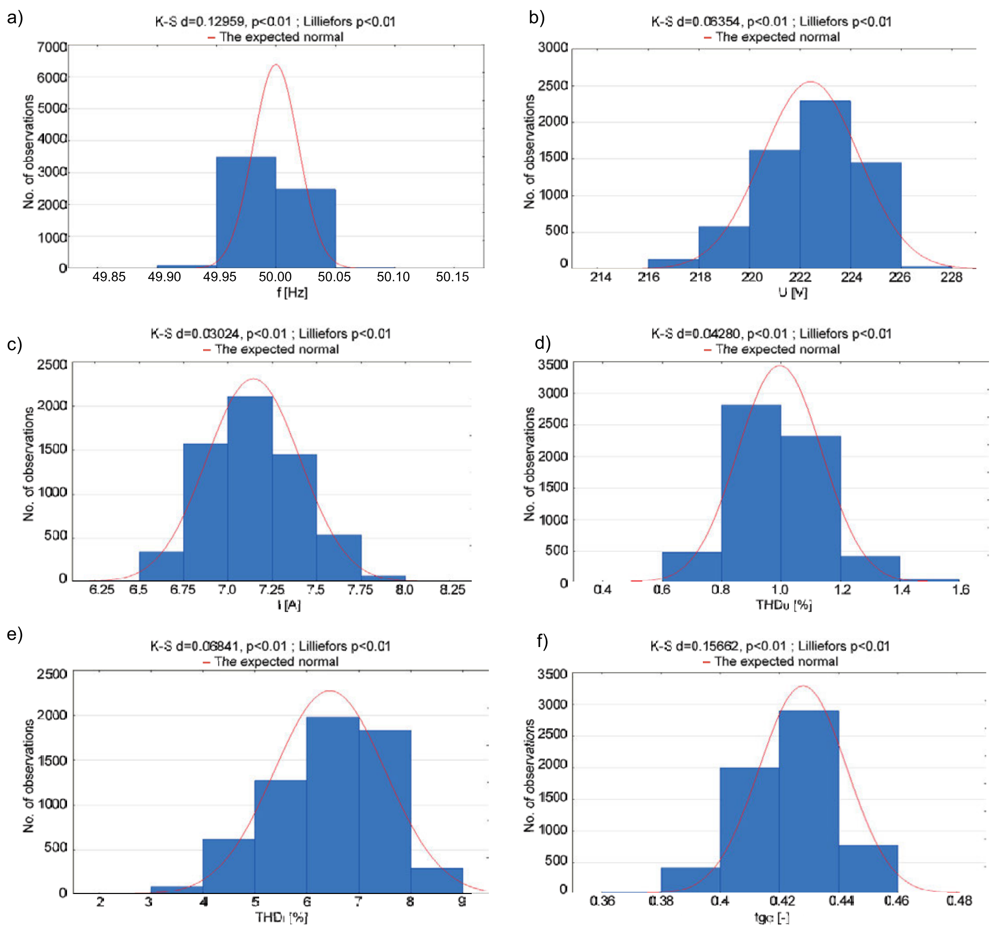

Fig. 2. Histogram of analysed parameters values approximated by a normal distribution: a) voltage frequency (*f*), b) voltage (*U*), c) current (*I*), d) total harmonic distortion of voltage (THD_U), e) total harmonic distortion of current (THD_I), f) power factor (tg(*φ*)); source: own study

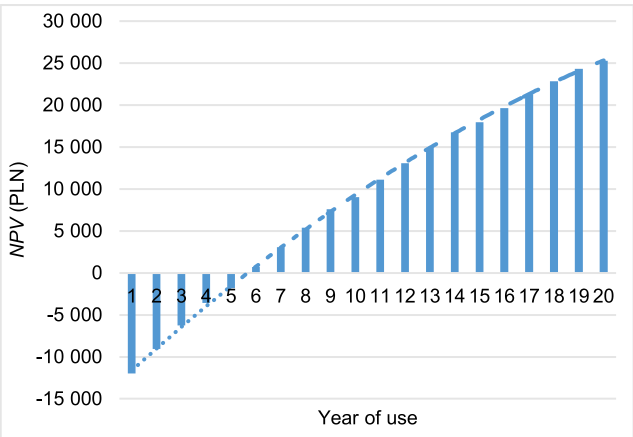

Fig. 3. Net present value (*NPV*) of the investment in the photovoltaic source in individual years of operation; source: own study

are two possibilities for obtaining power supply. The first is to build a connection to a medium voltage line. However, this is a costly investment, which depends mainly on the distance of the area from the nearest power line. The cost of building 1 km of connection is approximately 100 thous. PLN. To this must be added the construction cost of an overhead transformer station, which amounts to about 70 thous. PLN. The significant advantage of this type of solution is high reliability and lack of need for constant service.

The second solution is to power the pump with a diesel generator. The purchase of a power generator with a capacity of not less than 3 kW, with electronic ignition, is an expense of approximately 3 thous. PLN. To this expense, one must add the costs of fuel and service. Assuming combustion at the level of 1 dm^3 per hour of the aggregate's work, it will be necessary to spend about 2 thous. PLN on fuel per year with the analysed system. Moreover, one should add the costs of oil change (at least once a year) and the costs of servicing the system (depending on the number of inspections the unit's failure frequency, and the length of the travel route). They may amount to as much as 4 thous. PLN per year. Assuming the length of operation of the irrigation system for 25 years, the total cost of power supply from the aggregate will amount to as much as 153 thous. PLN. Additionally, this type of power supply is the most failure-prone and requires frequent inspections and operational repairs.

The use of photovoltaic systems to power irrigation systems operating in areas remote from electricity grids is not a new topic. It has been addressed many times in the pages of various journals [KHAN 2012; MUHAMMAD *et al.* 2014; WANG *et al.* 2022]. However, the authors of these works did not pay special attention to the quality of the energy used to power the pumps. One can find studies [WANG *et al.* 2019] on voltage instability caused by the operation of induction motors. AMMAR *et al.* [2022] described how to improve the efficiency of a photovoltaic water pumping system under partial shading conditions. SHCHUR *et al.* [2021]

focused on the controllability of water pumping. However, these are theoretical analyses, not supported by laboratory tests. Some of the works show the cooperation of photovoltaic sources with dedicated consumer devices concern systems cooperating with the power grid [PADOLE *et al.* 2022]. The considerations presented in this paper were aimed at showing how to select a photovoltaic pumping system and to demonstrate its economic efficiency. However, the most important point of the conducted research and analysis was to make a prototype of such a system and to measure the parameters of the voltage supplying the pumping system – to determine the quality of electricity supplied from the photovoltaic grid system to the water pump. This is a very important topic, as the efficiency and lifetime of the pumps depend on their electromagnetic and electrical compatibility with power sources.

CONCLUSIONS

Due to the increasing occurrence of periods with water scarcity, farmers are forced to look for solutions to prevent this problem. The ideal solution seems to be drip irrigation, which is the most efficient of all irrigation types. Unfortunately, agricultural land is often located far from urbanised areas where water and electricity are readily available. This necessitates the construction of one's own water intake (in the form of a deepwater pump or an aboveground tank) or the use of natural water reservoirs (which is severely restricted by water legislation). A source of electricity is also needed to power the pumps. The combustion engines commonly used for this purpose require a small initial investment but are characterised by very high operating costs, high failure rates, and a significant environmental impact. The optimal way to power irrigation pumps is to use a mini photovoltaic power plant with energy storage. Although it is an expense of about a dozen to several dozen thousand PLN (depending on the power of the irrigation pumps), its later operation and maintenance costs are small (it is mainly required to carry out a technical inspection once every five years). The return on investment in a renewable energy source, depending on the type of irrigated plants and the number of drought periods, should not exceed several years. Field tests carried out on the built prototype showed the correct quality parameters of the voltage supplying the irrigation pump, which ensured its proper operation.

The tested system was mainly characterised by low content of higher harmonics (the value of *THD* coefficient did not exceed 10% in current and 1.7% in voltage). Maintaining such values allows the pump to be powered with a voltage very close to the sinusoidal waveform, which guarantees the maintenance of an adequate life of the device. This allows us to assume that such systems could perform well in real conditions. It should be remembered, however, that the presented solution is dedicated mainly to powering pumps irrigating small areas.

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