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Experimental Analysis of a Solar-Powered Centre Pivot Irrigation Site and Hyperlocal Evapotranspiration Data

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In countries such as Hungary, the utilisation of solar energy for irrigation represents a pivotal consideration. As a consequence of climate change, the crop rotation period is characterised by an increased availability of sunny and bright days. A paucity of cloud cover and precipitation has distinguished recent Hungarian summers. The necessity for adaptation in agriculture, which produces raw materials for food, will also arise as a result of the increasingly extreme weather conditions caused by global climate change. The irrigation of crops is a vital process during increasingly frequent periods of drought. However, the cost of irrigation can be expected to rise significantly in response to elevated energy prices. The objective of this research is to ascertain the viability of utilising irrigation systems powered by renewable energy sources. Hungary is on the verge of a significant investment in its national irrigation infrastructure. Nevertheless, the investment may prove to be unprofitable as a result of the expense associated with the energy required for irrigation. In three research areas, the energy production of the solar farms associated with the pivot irrigation system has been monitored, and the hyper-local evapotranspiration data has been calculated. Regression analysis was employed to evaluate the results. The findings indicate that the dataset is significant. The field results and analysis can be useful for upfront investment in such projects. Precipitation, as a third variable, has a positive impact on the relationship between energy production and crop water demand.

1. Introduction

To date, only a limited number of practical studies have been published on solar irrigation systems of this kind. Consequently, the publication of articles that adhere to the highest scientific standards on this topic will be of great importance. The development of irrigation in Hungary is considered a national strategic issue, given that a significant proportion of the country's GDP is derived from agricultural production and related sectors, including mechanical engineering, food processing, and the agricultural banking sector. Irrigation became unpredictable with the rise in energy prices. In some cases, in Hungary, growers could only have contracts with their electricity supplier at a price of 0.6 EUR/kWh for up to a year. There has also been a similar increase in the price of diesel oil, which has almost doubled over the last few years. The result of these trends has been a 50-100 % increase in irrigation costs. In irrigation terminology, the simplest way to express the cost of irrigation is to use the ratio EUR/mm. This expresses the cost per unit of water irrigated. It is a way of expressing the cost of irrigation on a large-scale farm. This upper limit can be as high as 6.25 EUR/mm. The lower limits are 3.25 EUR/mm. Under these conditions, it is possible to produce profitably with the help of self-produced energy, which is independent of large energy exporters and the world's political situation. The application of photovoltaics at irrigation sites has attracted the attention of professionals in the agricultural irrigation industry. Nevertheless, the viability of solar-powered irrigation hinges on a nuanced consideration of technical and economic factors. The viability of such systems is contingent upon a number of factors, including climate data, aquifer depth and cost (Kelley et al., 2010). The pumping of water at a specified pressure and flow rate represents a pivotal aspect of irrigation. The utilisation of conventional pumping energy sources, such as diesel or gas, has been identified as a significant contributor to the greenhouse effect. In this context, solar pumping emerges as a potential alternative (Ramli and Jabbar, 2022). Typically, irrigation pumps utilise diesel or gas as their energy source, although grid-

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connected electricity is sometimes utilised as an alternative. Solar pumps may be considered as an alternative solution for replacing these energy sources (Pinto et al., 2021). In contrast, solar-powered irrigation represents a solution that extends beyond the mere watering of plants. It also constitutes a crucial step in the greening of agricultural energy use (Ali and Madad, 2018). In addition to the return on investment (ROI), the social return on investment (SROI) is a significant consideration in the context of solar irrigation. Such investments yield not only economic benefits but also social advantages. Such investments assist in the reduction of carbon emissions, which in turn mitigates the adverse effects of noise at irrigation facilities, minimises soil vibration, and notably, curtails the emission of pollutants into the atmosphere (Suriyachai et al., 2024). The analysis of energy production and water demand data series can also be a useful factor in the comparison of off-grid and grid systems. It has been demonstrated that no energy storage capacity is necessary for off-grid solar irrigation systems with a power output of up to 11 kW. In cases where the capacity exceeds this threshold, it is advisable to undertake a cost-benefit analysis of grid connection versus the installation of an energy buffer, given that the latter option will entail a higher initial investment (Bruning et al., 2023). Recent studies have shown that PV water pumping technology is a reliable and economically viable alternative to electric and diesel water pumps for irrigating agricultural crops (Sharma, 2022). Conversely, the recent surge in energy prices is increasingly diminishing the return on investment (ROI) of solar energy investments. From a governmental viewpoint, the utilisation of electricity generated on-site represents a significant motivating factor. The utilisation of solar-powered pumps and solar pump-based irrigation represents a viable solution for the on-site utilisation of energy. Peak production and peak demand could be met, reducing the necessity for governmental electricity planning to invest significantly in the generation of energy to offset fluctuations in supply and demand. In Hungary, the potential for irrigated areas with a positive return on investment is approximately double or triple the current area. It is recommended that programmes be implemented to enhance irrigation investments. These investments will have a significant impact on the future of irrigation management in Hungary. In light of these prospective investments, it would be prudent to consider solar energy as a potential source for facilitating the movement of water to plants. Hungary is a country with a limited supply of oil and other conventional energy sources. The cost of solar energy is decreasing, and the country is well-suited to the production of photovoltaic energy. In many instances, the financial burden associated with centre-pivot corner arms can result in the exclusion of specific areas from irrigation investment considerations. The phenological phases, average yields and harvest dates of non-irrigated corner areas are significantly different. Recent research indicates that non-irrigated areas could be readily converted to solar panels, facilitating their utilisation (Roberts, 2011). In order to define the crop water requirements, evapotranspiration was employed as the analytical tool. Evapotranspiration (ET) is one of the most useful hydrological fluxes for maintaining the water balance of terrestrial ecosystems. The reliable and accurate quantification of changes in evapotranspiration (ET) is essential for effective irrigation management, crop yield prediction, environmental assessment, ecological modelling and solar energy schemes (Srivastava et al., 2020). Further studies have shown that based on the solar irradiance required to operate a solar irrigation system, a solar pumping system is technically feasible in regions where the average daily solar irradiance is between 4 kWh/m^2-day and 5 kWh/m^2-day in the summer period. In principle, a solar pumping system requires an average daily irradiation of at least 4.0 kWh/m^2/day and more than 3.5 kWh/m^2/day in the month with the least sunshine. (Diop, 2020) Statistics show that these limits are met in Hungary. (Naplopo, 2024.) In light of this evidence, subsequent research has indicated that the deployment of solar energy for irrigation purposes has the potential to reduce or even eliminate energy costs for farmers. Furthermore, it represents a viable option for supplying energy in isolated areas. Additionally, the adoption of renewable energies offers a low GHG emissions alternative to conventional electric energy or diesel engines, contingent upon the necessary adaptations to accommodate a variable energy supply. Solar irrigation in regions with adequate solar irradiance represents a viable option for utilising renewable energy sources, enhancing the sustainability and profitability of irrigated agriculture. (Mérida García et al., 2018) A recent study has demonstrated that the replacement of grid electricity with solar energy can result in a return on investment within a 31-month period, which makes it a highly attractive proposition in comparison to other investment opportunities within the agricultural sector. (Martínez-Solano et al., 2024) The literature indicates that the environmental, social and economic conditions in Hungary are becoming increasingly conducive to the research and application of solar irrigation as an alternative.

2. Materials and methods

In comparison to the total irrigated area in Hungary, operational solar pumping projects are relatively uncommon. Each pumping station in Komárom-Esztergom County has a solar-powered irrigation system in operation. The project is situated in three locations within the county: Bana, Tata and Ács-Vaspusta. This investment represents one of the most substantial solar centre pivot irrigation projects in Europe currently in operation.

Each pumping station is connected to the centre pivot located in the surrounding fields. A contemporary remote monitoring system, comprising corner irrigation, has been installed at the centre pivots. Variable frequency drives (VFDs) have been installed at the pump stations. The variable frequency drives are responsible for optimising the pressure, reducing energy consumption and preventing the pipeline system from becoming over-pressurized. The sites were visited on a regular basis throughout the course of the measurement process. Photographic documentation of the operational status and phenological phases of the plants was also undertaken. This data will be used for further research. The meteorological stations were maintained on a biannual basis.

2.1 Monitoring of electric energy production

The solar panels are connected to the electrical grid, and the energy production is subject to continuous monitoring. The data has been retrieved from the eSolar platform. In order to facilitate correlation analysis with evapotranspiration, the data was collected on a daily basis. The data is presented in the format of kWh/day produced, which characterises the amount of electricity consumed daily (Oliveira et al., 2009). The measurement in kWh/day represents the daily production by the solar panels. The data collection period aligns with the typical growing season for summer crops and the potential irrigation period in Hungary. The data were collected between 1 April and 31 August. The investigation was conducted in 2023.

2.2 Monitoring of climatic data

In order to obtain hyper-local weather data, three meteorological stations equipped with the requisite technology have been established in the three locations. The meteorological stations were manufactured by Pessl Instruments, a company specialising in meteorological equipment, under the brand name METOS and the type IMT300 MWS. Stations are equipped with sensors to calculate evapotranspiration data. (Metos, 2024)

The meteorological stations are equipped with the following sets of sensors: a pyranometer, a wind speed and gust sensor, an air temperature sensor, a relative humidity sensor, and rain gauges. The calculation of evapotranspiration is based on the Penman-Monteith equation, which is a method described by the FAO 56 (Allen et al., 1998). This method models data on potential evapotranspiration, which represents the water requirements of the crop and the daily loss of water from the field. The unit of measurement is the mm/day. Precipitation data are collected via automatic rain gauges and are also expressed in mm/day. Precipitation data are collected in order to facilitate the linkage of irrigation decisions to the actual conditions of rainfall. For instance, instances of cloud cover may result in both rainfall and the generation of electricity in valleys.

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma(900/(T+273))U_2m(es - ea)}{\Delta + \gamma(1 + 0.34U_2m)} \qquad (1)$$

where

ET_0 - Reference evapotranspiration, Water volume evapotranspired (mm day^{-1})

Δ - Rate of change of saturation specific humidity with air temperature. (Pa K^{-1})

R_n - Net irradiance (MJ m^{-2} day^{-1}),

G - Ground heat flux (MJ m^{-2} day^{-1}),

T - Air temperature at 2m, K

U_{2m} - Wind speed at 2m height, m/s

es - saturation vapor pressure, kPa

ea - actual vapor pressure, kPa

γ - Psychrometric constant ($\gamma \approx 66$ Pa K^{-1})

2.3 Data collection and analysis

The data set comprised three variables: energy generation (kWh/day), reference evapotranspiration (ET_0 in mm/day) and precipitation (in mm/day). From a distributional standpoint, an investigation was conducted into these data. The objective of the study was to ascertain the most appropriate analytical techniques for the data in question. Having established that the data are normally distributed. The analysis was conducted using regression analysis. The results are presented below.

Table 1: Bana site regression analysis results

	Coefficients	Standard Error	t Stat	P-value	Lower 95 %	Upper 95 %	Lower 95.0 %	Upper 95.0 %
Energy production kWh/day	100.675	14.988	6.717	3.666E-10	71.058	130.292	71.058	130.292
ET_0 mm/day	58.430	4.069	14.360	6.616E-30	50.390	66.471	50.390	66.471
Precipitation mm/day	-1.950	0.728	-2.680	8.187E-03	-3.388	-0.512	-3.388	-0.512

Table 2: Tata site regression analysis results

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Energy production kWh/day	135.727	12.466	10.888	1.04158E-20	111.095	160.36	111.10	160.36
ET_0 mm/day	19.938	2.631	7.578	3.37186E-12	14.739	25.14	14.74	25.14
Precipitation mm/day	-4.298	0.872	-4.932	2.13895E-06	-6.020	-2.58	-6.02	-2.58

Table 3: Ács-Vaspuszta site regression analysis results

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Energy production kWh/day	72.241	12.7648	5.659	7.48916E-08	47.018	97.463	47.018	97.463
ET_0 mm/day	57.056	3.4636	16.473	1.8413E-35	50.212	63.900	50.212	63.900
Precipitation mm/day	-2.866	0.7639	-3.752	0.000250441	-4.376	-1.357	-4.376	-1.357

3. Results and discussions

In all three cases (Table 1-3), the R^2 values were between 0.44 and 0.71, indicating that other factors exert a minimal influence on the variables. In each case, the standard errors were found to be sufficiently small in comparison with the coefficients. The P-value was found to be statistically significant, indicating that the variables are indeed meaningful. Consequently, a negative correlation was identified between precipitation (higher cloud cover) and energy produced (Table 1-3). Fortunately, the countervailing effect of these two factors does not have a negative impact on investment intensity. One of the conclusions that can be drawn from the results is that solar water irrigation represents one of the most advantageous renewable investments, given the correlation between energy availability and crop water demand. Such an investment does not exert as much strain on the electricity grid, as it requires less buffer capacity to operate. The social benefits of this technology assist in the advancement of sustainable farming practices through the reduction of emissions. The objective of the research was to provide producers with data that can be used in planning. It was essential to process the input data utilised in irrigation planning in order to integrate the findings derived from these sources. Utilising the extant knowledge, an equation has been formulated whereby the energy demand of an irrigation plant can be readily planned, taking into account the findings of the research. The following equation is provided for calculating the capacity of a grid-connected solar plant for such investments. In Hungary, the typical daily application rate is between 8 and 10 mm/day. Furthermore, the actual operational time is less than 24 h, with an average of 16 h/day. In the context of hydrology, hydraulic head refers to the pressure required by a system at the pump station.

$$Sp = (R_h*(A_{mm}*A*10/R_h)*P_{sh})*H/R \quad (2)$$

P_{sh} - Shaft power needed for pump 1 m^3 at 1 m head at 60 % pump efficiency, 0,00045 kW

A_{mm} - Daily center pivot application rate, mm/day

A – Irrigated area, h

R_h - Planned running time of pivot/day, h

H - Hydraulic head, m

S_P - Solar power production need, kWh/day

R – Multiplier R

The question of oversizing the systems by multiplying R is dependent upon the selling and buying price of the electricity generated, as well as the initial price of the solar investment. Following an analysis of the data, it can be seen that if the equation is applied without the R-number, energy production will be in line with water demand, with minimal electricity being sold to the grid.

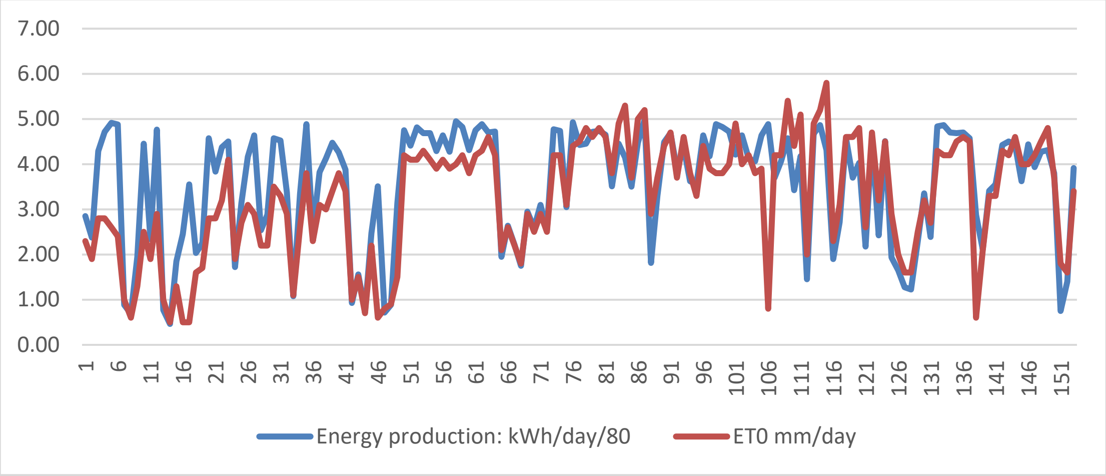

Figure 1: Visualization of Solar energy production and potential evapotranspiration in the same crop production site at Bana pump station. 80 is the ratio between kWh/day AVG and ET0/day AVG.

4. Conclusions

Following the analysis of the data, it became evident that a detailed examination of the data series comprising the extracted variables would be beneficial. A future, more extended analysis of this data may assist in understanding the context for practical sizing, facilitating the accurate sizing of solar irrigation systems.
The analysis indicates a positive complementarity between the energy production of the irrigation systems and both the daily water demand and the periods of rainfall. A strong correlation is evident in Figure 1, which supports the investment in solar irrigation technology. Other alternatives like nuclear energy or fossil fuel use come with more waste of resources and also with several pollution and environmental risk. The formula Eq(2) and the correlations between the data will prove invaluable in the future for the accurate sizing of solar irrigation systems in Hungary or EMEA. A limitation of the research is that it was only feasible to collect usable data from all three areas in the same time series during a single season. It is regrettable to report that the implementation process for some centre pivot irrigation systems has been delayed from 2020 to January 2023. A further limitation is that the actual evapotranspiration of the plants was not measured. This would, unfortunately, constitute an additional complication in the analysis of the correlations. It may be of interest to consider the potential benefits of running an ET model that includes the crop factor in the future. It should be noted that there may be slight discrepancies between the evapotranspiration of crops (ETc) and the reference evapotranspiration (ET_0). Nevertheless, the application of modelling techniques to assess crop evapotranspiration presents a significant challenge. This is due to the fact that crop evapotranspiration is subject to a multitude of variables and is influenced by the specific crop species and planting time.

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