

Agrivoltaic Solutions as an Example for Promoting Cost-Effective and Profitable Farming through Renewable Energy in Libya

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ABSTRACT

The purpose of this study is to assess the potential of both solar and wind energy in Az-Zāwiyah, Libya, to optimize the resource use, ensure energy security, and lower the costs in the agriculture sector. The main findings show that wind energy's potential is limited; however, the area has strong Solar Radiation (SR), making it highly suitable for Photovoltaic (PV) systems. Additionally, the feasibility of integrating an agrivoltaic system into greenhouse farming is explored. The results indicate that the proposed agrivoltaic system could generate significant energy, especially during spring and summer, with outputs of 31.6 MWh and 31.1 MWh, respectively, and high-capacity factors of 21.05% and 20.72%. The Simple Payback Period (SPP) is approximately 7 years, and the average Levelized Cost of Energy (LCOE) is 7.02 cents/kWh, demonstrating the system's economic viability. Implementing renewable energy through agrivoltaic substantially reduces the electricity costs for the greenhouse operations, increasing profitability. To achieve system profitability, the electricity price should be around \$0.065/kWh. The key conclusion is that the agrivoltaic systems can potentially enhance the energy efficiency and maximize the profits in Libyan greenhouse farming. Ultimately, this research aims to show farmers the advantages of using renewable energy in agriculture. The study emphasizes how solar energy can be integrated to foster sustainable farming practices. It is proposed that educational seminars and workshops be organized to provide farmers with the necessary information to adopt these renewable technologies and ensure their long-term sustainability.

Keywords-solar energy potential; wind energy potential; agrivoltaic system; Libya; techno-economic feasibility

I. INTRODUCTION

Fossil fuels currently power most agricultural activities, which increases the Greenhouse Gas (GHG) emissions and

contributes to the climate change [1, 2]. Agri-food chains utilize nearly 30% of the world's energy and account for 19%–29% of the annual global GHG emissions, according to the "Consultative Group on International Agricultural Research"

(CGIAR), while cultivation activities alone account for 20% of the total Carbon Dioxide (CO₂) emissions [3, 4]. The production of electricity accounts for 78.7% of the carbon footprint of all agricultural practices [5]. The productivity of the agriculture sector primarily depends on the three main constituents: energy, water, and land resources. According to [2], the primary resources that affect the agricultural sector's production are energy, water, and land. Besides, as fossil fuels and electricity prices have been steadily rising and significant GHG emission reductions are required, there is a need to improve the energy efficiency, which has led to a need for alternative energy sources [6-8]. Using renewable energy sources can help increase the crop yields by reducing the reliance on non-renewable resources [9, 10]. Among these sources, the solar and wind energy are abundant and environmentally friendly. A promising approach to meeting the agricultural energy demands is using renewable energy systems [11]. However, the solar and wind energy are inherently variable, which can reduce their efficiency. Despite this, they can operate reliably, both as standalone systems and when connected to the grid [12-14]. To address variability, Hybrid Renewable Energy Systems (HRES) are often used. These systems integrate two or more renewable sources and can function independently or in conjunction with the grid [11, 15, 16]. In such systems, the solar and wind energy can be generated simultaneously or in sequence, depending on the availability and system design [17, 18].

A. Energy Situation in Libya

Libya's electrical infrastructure has been suffering from a crucial political crisis, conflict, and a lack of funding [19]. The country's electrical needs are excessive for the national system, which is operated by the General Electrical Company of Libya (GECOL) [19-21]. Numerous issues, such as a lack of fuel, damaged infrastructure, and maintenance issues, have contributed to frequent blackouts and power outages. As the situation deteriorated, grid-wide blackouts increased in frequency in 2020, significantly damaging the electrical infrastructure and escalating civil unrest [21]. Additionally, the decrease in gas production has made the electrical situation worse. Besides, the fuel shortages have forced GECOL's natural gas-fired power facilities to rely more on imported diesel, an unsustainable and costly solution [22]. The ongoing electrical crisis in Libya affects all sectors of the economy [21, 23]. Frequent power outages have forced many households to rely on alternative sources, like diesel generators. However, these solutions are costly and environmentally harmful, exacerbating the existing problems. This situation has deterred investment and reduced the industrial productivity. The healthcare sector has also suffered, with hospitals and clinics being unable to maintain consistent power to run the essential medical equipment. Among all sectors, agriculture is the most severely affected. Although it contributes less economically than oil or gas, agriculture is crucial for the food security and rural livelihoods [24]. Farmers depend on electricity for irrigation, storage, and crop processing. Power outages disrupt these activities, leading to lower yields, post-harvest losses, and spoilage of perishable goods due to inadequate cold storage. Environmental challenges, like droughts and floods, have further worsened the situation, damaged rural infrastructure and

made electricity and water supplies even more unreliable. As a result, many farmers struggle to sustain operations and are forced to use diesel pumps and generators, increasing costs and undermining the efforts toward sustainable, climate-resilient agriculture [21, 24-26]. Recognizing the need for energy diversification, Libya has begun integrating renewable energy into its national energy strategy. The Libya Renewable Energy Strategic Plan (2013-2025) aims to have generated 10% of the country's electricity from renewable sources by 2025 [27, 28]. The more recent National Strategy for Renewable Energy and Energy Efficiency (2023-2035) has set a goal of 4 GW of installed renewable capacity of 2035 MW-600 MW from wind and 3.3 GW from solar PV [29]. According to the Global Solar Atlas, Libya has a solar energy potential of 6.5 kWh/m²/day [30]. Estimates suggest that Libya holds 20% of the Mediterranean region's total solar energy potential, approximately 332 TWh/year [31], and up to 1,050 TWh annually of the North Africa's solar capacity [32]. In line with these potentials, the Libyan company Solar Energy Solutions (SES) announced the development of a 50 MW solar plant in Sabha in 2019 [33], followed by a government-backed plan for a 500 MW facility in the same city in 2020 [34]. These initiatives aim to reduce the environmental impact while improving the energy reliability across the country.

B. Importance of the Study and Research Aim

Libyan agriculture is facing growing challenges due to the limited resources, high energy costs, and unreliable power supplies. These issues threaten the sustainability of farming operations, especially those that depend heavily on electricity for irrigation and greenhouse climate control. To provide real-world context, this study focuses on a case study farm located in eastern Az-Zāwiyah. The farm spans two hectares and includes thirty greenhouses, each 400 m² in size, where crops, such as cucumbers, tomatoes, and peppers, are cultivated. A mixed-methods survey was conducted with local farmers, combining qualitative (open-ended) and quantitative (multiple-choice) questions to gather insights into the energy and water challenges. This study responds to an urgent need by exploring environmentally friendly energy alternatives for agricultures specifically agrivoltaic systems, which combine the solar power generation with crop production on the same land. The research evaluates Libya's solar and wind energy potential and examines the feasibility of implementing agrivoltaic systems in agricultural settings. Given Libya's favorable climate, the study analyzes the capacity of solar and wind technologies to generate electricity for farming needs. The goal is to demonstrate how renewable energy can reduce costs, improve efficiency, and enhance farm profitability. By analyzing the energy outputs and economic returns, the study provides practical recommendations for adopting sustainable practices. It underscores the strategic value of integrating renewable energy into agriculture as a solution to Libya's energy and resource challenges. The selected case study farm serves as a valuable testbed for evaluating the real-world benefits of agrivoltaics. Ultimately, the findings aim to guide farmers, policymakers, and stakeholders in adopting sustainable energy solutions to transform the agricultural practices in Libya and similar regions.

II. MATERIALS AND METHODS

A. Study Area

Az-Zāwiyah, which is situated northwest of Libya's Mediterranean Sea coast, has been an important center for both the agricultural and urban growth. The climate of this area is Mediterranean, with hot, dry summers and warm, rainy winters. Az-Zāwiyah experiences winter temperatures of about 10 degrees and summer temperatures of over 30 °C on average. Most of the year's rainfall, which ranges from 250 mm to 400 mm, occurs during the winter. The region's agricultural activities relied mainly on irrigation due to the inconsistency and limited extent of rainfall. Most of Az-Zāwiyah's water resources are derived from shallow groundwater aquifers, which are severely stressed by pollution and over-extraction. The national blackout crisis in Libya, which also affects Az-Zāwiyah, exacerbates these issues. Voltage variations and current power outages seriously impair the crop-growing processes. These have a significant impact on agricultural businesses that rely on steady energy for greenhouse operations, irrigation, and cooling.

B. Situation of the Agriculture Sector and the Selected Farm

A specific case study farm located on the eastern side of Az-Zāwiyah was selected to focus on sustainable energy solutions in agriculture. The farm occupies two hectares and contains 30 greenhouses, each measuring 400 m². The soil is semi-sandy with slight clay content, making it ideal for greenhouse cultivation of crops, such as peppers, tomatoes, and cucumbers. However, the farm depends heavily on electricity to operate irrigation systems and maintain optimal internal conditions within the greenhouses, making it particularly vulnerable to the region's inconsistent power supply. Following an extensive review of relevant literature, a targeted survey was developed and conducted across selected agricultural areas to gather data and first-hand insights from farm owners. The survey employed a mixed-methods approach, integrating both qualitative and quantitative techniques to develop an understanding of the challenges and opportunities encountered by the local agriculture. Through a combination of open-ended and multiple-choice questions, the survey collected both detailed personal feedback and structured responses. The results revealed two key insights. First, farmers identified desalination systems as a promising solution for improving the quality of irrigation water. When combined with existing groundwater sources, these systems could significantly enhance the water reliability and safety for agricultural use. Second, there was a strong interest in using renewable energy, particularly solar and wind, to power the desalination processes. This would reduce the reliance on costly conventional electricity, lower operational expenses, and would support more sustainable farming practices. By cutting the energy costs, farmers could potentially boost the crop production and increase their profit margins. These findings reflect a broader recognition among farmers of the transformative potential of renewable energy and advanced water treatment technologies in the agricultural sector. The case study farm exemplifies the interconnected challenges faced by Libyan farmers in the energy-water-agriculture nexus. At the same time, it offers a practical testing ground for

evaluating how solar energy can deliver stable, affordable electricity to support sustainable greenhouse farming in the region.

C. Dataset

According to [21], all satellite-based datasets are suitable for a preliminary solar resource assessment, but ERA5-Land is the most effective for evaluating the wind resources in the selected location. ERA5-Land is a high-resolution global reanalysis dataset developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). It focuses specifically on the land conditions and how atmospheric factors affect them, following the structure of the broader ERA5 reanalysis system. With a spatial resolution of approximately 9 km and hourly temporal resolution, ERA5-Land provides detailed data on the surface, hydrological, and atmospheric variables. This dataset is especially valuable for land-based applications, such as environmental monitoring, hydrology, and agriculture. Its modeling framework integrates a wide range of observational inputs, including satellite and ground-based data, enabling higher accuracy in estimating the weather and climate variables at local and regional scales. As a result, ERA5-Land is a highly reliable source for agricultural studies, particularly for analyzing the climate variability's impact on the crop yields or optimizing the irrigation strategies.

D. Wind Energy Assessment

Understanding wind characteristics is essential for evaluating the viability and potential of wind energy in each area to use it efficiently [35]. Therefore, the characteristics of wind speed and the wind energy potential in a location are estimated using the Weibull distribution function. The Weibull distribution function is a helpful tool for determining the amount of electricity that a specific wind turbine produces [36]. It is represented as a probability distribution in (1) and a cumulative distribution in (2):

$$f(v) = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (1)$$

$$F(v) = 1 - \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (2)$$

where v is the wind speed value in m/s, and k and c are the shape and scale parameters, respectively.

Several techniques have been employed to find the Weibull parameters. In this study, the Maximum likelihood Method (MLM) is used [37]. The k is estimated using numerical iteration in MLM, using:

$$k = \frac{1}{\frac{\sum_{i=1}^n v_i^k \ln(v_i)}{\sum_{i=1}^n v_i^k} - \frac{\sum_{i=1}^n \ln(v_i)}{n}} \quad (3)$$

Numerical iterations are carried out using (3) and an assumed initial k until the previous iteration's k value is sufficiently close to the current k value. Once the k has been determined, as shown in (4), the known value of k can be used to find c :

$$c = \left(\frac{1}{n} \sum_{i=1}^n v_i^k\right)^{1/k} \quad (4)$$

where v_i represents the observed wind speed and n represents the total number of observations for wind speed data. Besides, the mean wind speed (\bar{v}) can be estimated using the Weibull parameters as shown in:

$$\bar{v} = c\Gamma\left(1 + \frac{1}{k}\right) \quad (5)$$

Furthermore, one of the most crucial measures of the wind potential for the wind farm design is the Wind Power Density (WPD) [38, 39]. WPD is used to evaluate the potential of the wind resources at a certain site, and is calculated by [40]:

$$\frac{P}{A} = \frac{1}{2}\rho c^3\Gamma\left(\frac{k+3}{k}\right) \quad (6)$$

where P represents the wind power, ρ is the air density ($\rho = 1.23 \text{ kg/m}^3$), A is the area in m^2 , \bar{v} is the mean wind speed in m/s , and Γ is the gamma function. Additionally, the average WPD at a height of 10 m is utilized to describe the wind energy potential at the specific location as follows [21, 40]: Poor ($\text{WPD} \leq 100 \text{ W/m}^2$); Marginal ($\text{WPD} \leq 150 \text{ W/m}^2$); Moderate ($\text{WPD} \leq 200 \text{ W/m}^2$); Good ($\text{WPD} \leq 250 \text{ W/m}^2$); and Excellent ($\text{WPD} \leq 300 \text{ W/m}^2$). In general, the standard height at which the wind speed data are gathered is 10 m above ground. The power law model is used to estimate the wind speeds at various hub heights and is defined by [23]:

$$\frac{v}{v_{10}} = \left(\frac{z}{z_{10}}\right)^{\frac{0.37-0.088\ln(v_{10})}{1-0.088\ln(z_{10}/z)}} \quad (7)$$

where v is the wind speed at the wind turbine hub height z , and v_{10} is the wind speed at the original height z_{10} .

E. Solar Energy Assessment

The potential for solar energy was assessed by classifying it according to the annual levels of the global SR. GSR is regarded as a crucial metric for evaluating the PV systems' capacity to generate electricity. Furthermore, the solar energy potential is categorized according to the annual value of GSR [35, 41] as: Poor (Annual SR $< 1191.8 \text{ kWh/m}^2$); Marginal ($1191.8 < \text{Annual SR} < 1419.7 \text{ kWh/m}^2$); Fair ($1419.7 < \text{Annual GSR} < 1641.8 \text{ kWh/m}^2$); Good ($1641.8 < \text{Annual SR} < 1843.8 \text{ kWh/m}^2$); Excellent ($1843.8 < \text{Annual SR} < 2035.9 \text{ kWh/m}^2$); Outstanding ($2035.9 < \text{Annual SR} < 2221.8 \text{ kWh/m}^2$); and Superb ($\text{Annual SR} < 2221.8 \text{ kWh/m}^2$).

F. Electricity Generated by PV System

A solar PV system's monthly energy output can be estimated by considering key factors, such as the installed system capacity, the peak sun hours at the location, and a derate factor that accounts for the combined effects of the component efficiencies, system losses, and environmental conditions [21]. The amount of electricity that a PV system is anticipated to produce can be estimated with this method. The monthly energy output in kWh is calculated by [21]:

$$E_M = N_d \times f_m \times \frac{H_c}{1 \text{ kW/m}^2} \times P_{IC} \quad (8)$$

where f_m is the average monthly derate factor or performance ratio, N_d is the number of days in the month, H_c is SR on the plane of the solar PV array in $\text{kWh/m}^2/\text{day}$ and P_{IC} is the solar PV installed capacity in kW.

G. Electricity Generated by the Wind System

Equation (9) provides an expression for the wind turbine's total power output (E_{wt}) [42]. In addition, a parabolic law (10), can be used to approximate the wind turbines' power curve [42, 43]:

$$E_{wt} = \sum_{i=1}^n P_{wt(i)} t \quad (9)$$

$$P_{wt(i)} = \begin{cases} P_r \frac{v_i^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} & (v_{ci} \leq v_i \leq v_r) \\ \frac{P_r}{v_r} & (v_r \leq v_i \leq v_{co}) \\ 0 & (v_i \leq v_{ci} \text{ and } v_i \geq v_{co}) \end{cases} \quad (10)$$

H. Economic Viability

The economic viability of installing a PV system is assessed in this study using a variety of financial factors. These offer a comprehensive view of the project's financial performance and include the SPP and the LCOE [21]. The SPP in (11) provides a quick estimate of how long it will take for the initial investment to be recouped by the system's energy savings or revenue, making it a useful tool for evaluating the investment risk and identifying the projects with faster returns:

$$SPP = \frac{\text{Investment cost}}{\text{Annual Saving}} \quad (11)$$

Furthermore, the LCOE in (12) represents the average cost per kWh of the electricity generated during the system's lifespan and accounts for all capital, operating, and maintenance costs. This metric is essential for evaluating the cost-effectiveness of a PV system compared to other energy sources and technologies, supporting informed decisions in long-term energy planning and investment. Collectively, these measures help stakeholders assess the short- and long-term financial sustainability of solar energy projects:

$$LCOE = \frac{C_o + \sum_{t=1}^n \frac{C_{i,t} + C_{O\&M,t}}{(1+i)^t}}{\sum_{t=1}^n \frac{E_t}{(1+i)^t}} \quad (12)$$

where C_o is the investment cost, n is the economic life project, $C_{i,t}$, $C_{O\&M,t}$, and E_t are the investment cost, involving the replacement cost, operation and maintenance cost, and electricity generated per year, respectively.

I. Carbon Mitigation Analysis

The proposed solar power plant's carbon mitigation analysis is estimated using the following methodology [44]:

- The greatest CO_2 emissions that the solar power plant might reduce are given by:

$$\text{CO}_2 \text{ mitigation by PV system} = \text{Annual energy generation} \times \text{Emission factor} \quad (13)$$

- Solar power plants cannot be fully regarded as emission-free power-producing systems. Therefore, it is necessary to estimate the amount of CO_2 released per kWh of the power generated by the solar plant. The emissions released from the PV plant are determined using:

$$\text{CO}_2 \text{ emission from PV system} = \text{Annual energy generation} \times$$

CO_2 mitigation by PV system (14)

- The net reduction in CO_2 emissions from the solar PV facility is computed using:

$$Net\ CO_2\ reduction = CO_2\ mitigation\ by\ PV\ system - CO_2\ emission\ from\ PV\ system \quad (15)$$

III. RESULTS AND DISCUSSION

A. Wind Energy Assessment Results

In this research, the daily wind speed data for the selected location were collected from 2010 to 2024. Based on the analysis, Table I presents the descriptive statistics of the mean daily wind speed data. The average daily wind speed was found to be 3.16 m/s, fluctuating between 2.57 m/s and 3.75 m/s. Moreover, it is found that the CV values, which fall between 3.99% and 16.75%, are comparatively small. All distributions are right-skewed, as indicated by the positive values of S. Besides, the K values range from -0.98 to 1.03. Additionally, the mean daily wind speed for each month and season is shown in Figure 1. It is observed that the highest and lowest wind speeds are 4.76 m/s in January and 1.87 m/s in October, respectively. Additionally, as illustrated in Figure 1, the wind speed is the maximum during the spring season and the minimum during autumn.

TABLE I. SPECIFICATION OF SUNSURF'S WT3 VERTICAL AXIS WIND TURBINE

Variable	Mean	SD	CV	Min	Max	S	K
Jan	3.75	0.45	12.08	2.98	4.76	0.33	-0.38
Feb	3.39	0.55	16.28	2.43	4.57	0.20	-0.22
Mar	3.29	0.52	15.77	2.05	4.54	0.37	0.63
Apr	3.38	0.37	11.07	2.73	4.29	0.74	0.23
May	3.23	0.44	13.48	2.61	4.38	0.71	-0.09
Jun	3.23	0.51	15.90	2.17	4.56	0.76	0.73
Jul	2.93	0.27	9.27	2.53	3.62	0.57	0.01
Aug	2.85	0.26	9.00	2.43	3.40	0.54	-0.42
Sep	2.79	0.32	11.50	2.13	3.34	0.07	-0.51
Oct	2.57	0.43	16.75	1.87	3.66	0.96	1.03
Nov	3.02	0.47	15.45	2.37	4.18	0.93	0.43
Dec	3.46	0.40	11.57	2.61	4.47	0.54	0.45
Winter	3.54	0.29	8.09	3.07	4.07	0.17	-0.98
Spring	3.30	0.31	9.47	2.76	4.11	0.52	0.33
Summer	3.00	0.20	6.73	2.71	3.45	0.89	-0.14
Autumn	2.78	0.25	9.08	2.40	3.44	1.00	0.63
Annual	3.16	0.13	3.99	2.92	3.49	0.35	0.04

SD: standard deviation; CV: coefficient of variation; Min: minimum, Max: maximum; S: Skewness; K: Kurtosis

The Weibull distribution function is utilized for analyzing the characteristics of the wind speed data. The Weibull parameters' value is depicted in Figure 2. The MLM approach was used to determine the values of k and c. According to the results, the values of k and c fall between 5.89 m/s-24.71 m/s and 2.76 m/s-3.95 m/s, respectively. The highest value of c was recorded in January, and the lowest was in October. Figure 3 illustrates the Weibull probability plots and frequency histograms of the chosen location's wind speed. Figure 4 shows the mean and WPD, which are computed using (5) and (6), respectively. According to the data, the mean's highest and lowest values were 2.57 m/s and 3.75 m/s, respectively. Moreover, the WPD values are found to have an average of 19.79 W/m^2 and fluctuate between 32.24 W/m^2 and 10.40

W/m^2 . According to the WPD values, the chosen site has a comparatively low wind energy potential and is classified as power class 1 (Poor ($WPD \leq 100\ W/m^2$)). Therefore, the best strategy to efficiently utilize the existing wind energy resources in these areas is by installing small-scale wind turbines.

B. Results of Solar Energy Assessment

The selected location's mean monthly variation in SR is portrayed in Figure 5. It is found that the SR values range from 84.75 kWh/m^2 (December) to 238.05 kWh/m^2 (July). The solar energy potential can be categorized based on the SR annual value. The estimated annual SR value is 2633.82 kWh/m^2 , indicating that the location is classified as Superb (Annual SR <2221.8 kWh/m^2). It can be concluded that the selected location is suitable for solar system applications.

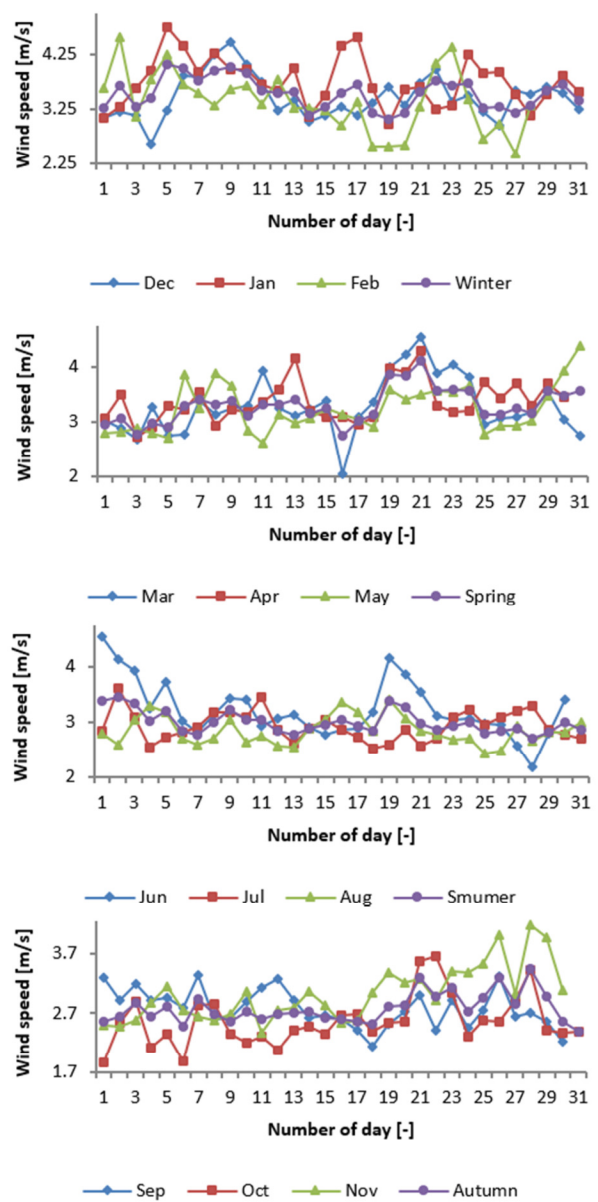


Fig. 1. Mean daily wind speed data for each month and season.

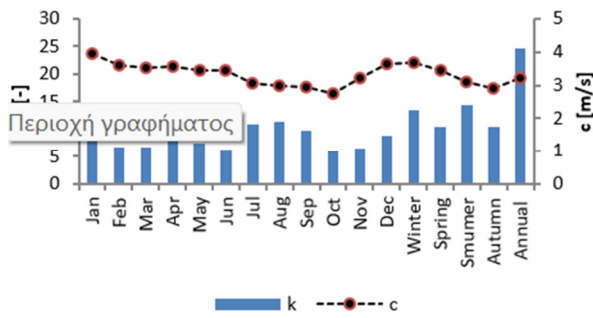


Fig. 2. Weibull distribution's parameters.

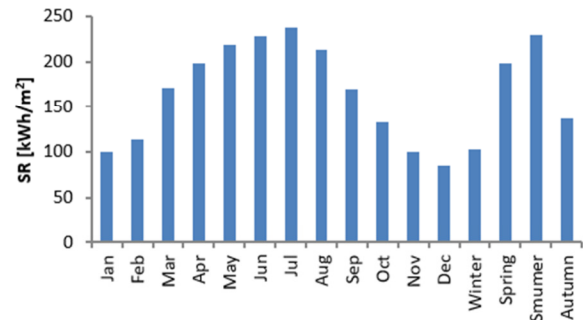


Fig. 5. Mean monthly value of SR for the selected location.

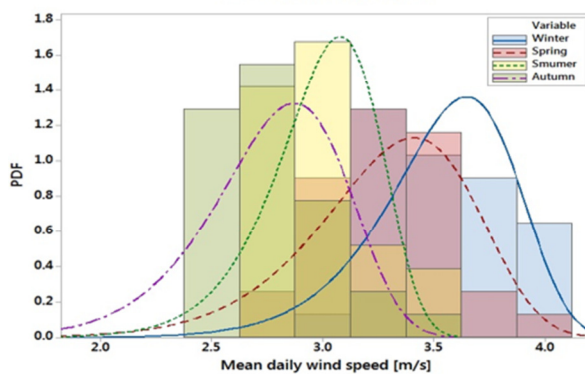
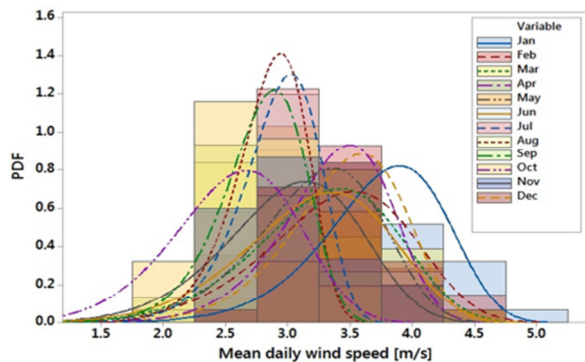


Fig. 3. Monthly rainfall data collected from different sources.

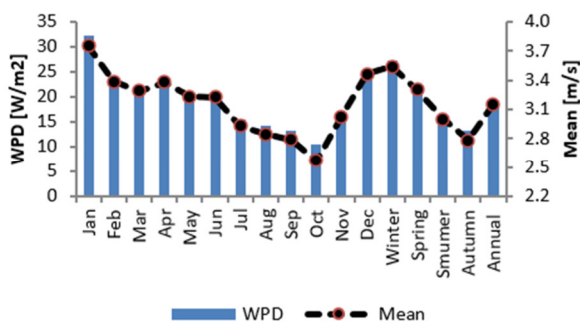


Fig. 4. Weibull distribution's parameters.

C. Summary

According to the findings, the maximum value of WPD was approximately 32.24 W/m², which is categorized as class 1 (poor). Additionally, the results indicate that the chosen region's solar resource is classified as Superb. In comparison to the potential of the wind energy, the chosen site has a vast amount of solar energy potential. Due to the high level of SR in the region, this area is, therefore, a suitable place for installing a solar system in the future.

D. Technical Sustainability

The selected farm relies on energy to power the irrigation equipment and control the greenhouse interior temperatures, making it susceptible to the disruptions caused by the region's unstable power supply. Figure 6 presents the seasonal variation of electricity needed to power the irrigation equipment and control the greenhouse interior.

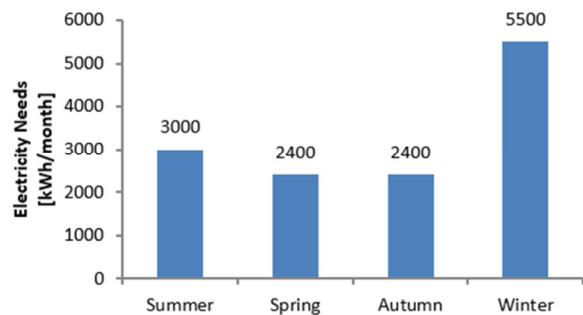


Fig. 6. Seasonal variation in electricity needs.

According to [45, 46], the capacity of a solar system can be estimated in terms of the minimum value of the SR and the daily power consumption, as shown in (16). Based on the findings, the capacity of the solar system is estimated to be around 68 kW:

$$P_{max} = \frac{E_{AC} P_i}{G_{SR} f_{PV} \eta_{inv}} \tag{16}$$

where P_i is the SR at STC in kW/m², G_{SR} is the global SR ($G_{SR} = 3.26$ kWh/m²/day), f_{PV} is the PV derating factor ($f_{PV} = 0.85$), E_{AC} is the daily power consumption (the average value of $E_{AC} = 183.33$ kWh/d), and η_{inv} is the inverter yield ($\eta_{inv} = 0.98$).

The term "technical sustainability" in engineering describes features of products that impact the effectiveness and performance. For a 68kW solar system, the total area required is 319 m². In this study, a free-standing mode system with a fixed tilt is examined. According to the PV Geographical Information System, the optimum slope and azimuth angles for the developed system are 35° and 0°, respectively. In this study, the JKM545M-72HL4-V model with a capacity of 545 W and efficiency of 21.13%, manufactured by Jinko Solar Company, is selected due to the high performance and reliability of generation of solar power as well as the market availability. Besides, two units of Multisolar Hybrid Inverter (MHI) with a capacity of 30 kW and 10 kW were selected in this study. Figure 7 shows the energy production of the fixed solar tracking system at the optimal orientation angles for the selected location. The results indicate a significant energy generation potential, with the highest output occurring in the spring and summer seasons, reaching 31.6 MWh and 31.1 MWh, respectively. Correspondingly, the capacity factors peak at 21.05% in spring and 20.72% in summer, as illustrated in Figure 7. Based on the data and comparisons with previous studies [47–49], the proposed solar PV system is technically feasible for installation and operation at the chosen site, as its annual energy production and capacity factor meet the acceptable standards.

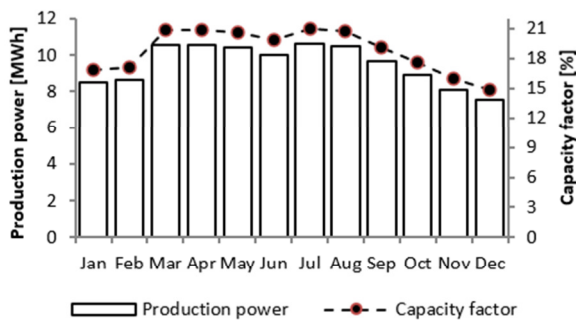


Fig. 7. Mean monthly value of SR for the selected location.

E. Economic Sustainability

Economic analysis is a critical step in determining the sustainability and profitability of a solar PV project. The initial cost of the developed system is estimated about 49526 USD, which includes 125 solar panels priced 201 USD each and inverter cost 9490.3 USD. Additionally, indirect expenses were accounted for to ensure a comprehensive evaluation: 8.6% for

installation and spare parts, 0.6% for engineering, development, and feasibility studies, and 3% for miscellaneous and contingency costs. The hybrid inverters are assumed to have a lifespan of 15 years. The local electricity rates significantly affect the economic feasibility of the solar PV systems [50–52]. In Libya, where the electricity rate is approximately 0.008 \$/kWh [53], the economic viability of the solar PV is limited. For the system to be profitable, the electricity price needs to be around 0.065 \$/kWh, which would provide a reasonable payback period and substantial cost savings over time. In this study, the LCOE and the SPP were used to evaluate the system’s economic performance. Figure 8 illustrates the SPP, representing the time required to recover the initial investment at the selected location. The longest payback period occurs during winter, while the shortest is observed in spring and summer. Based on annual energy production, the estimated SPP is approximately 6.68 years, indicating that installing PV systems in the area is economically attractive. Furthermore, the LCOE values range between 1.74 cents/kWh and 8.03 cents/kWh, as displayed in Figure 9. These findings align with those of [54, 55], where the PV system LCOE values ranged from USD 0.0199 \$/kWh to 3.165 \$/kWh. Therefore, the results of this study are consistent with those of the existing literature.

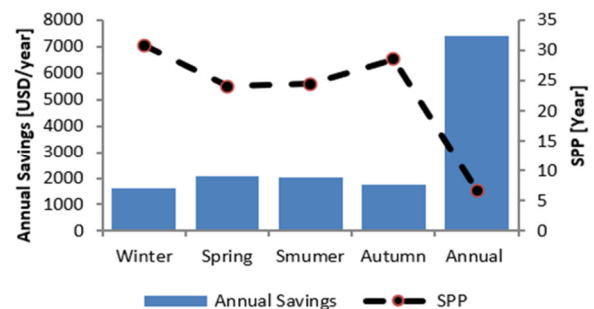


Fig. 8. Estimated SPP value for the developed system.

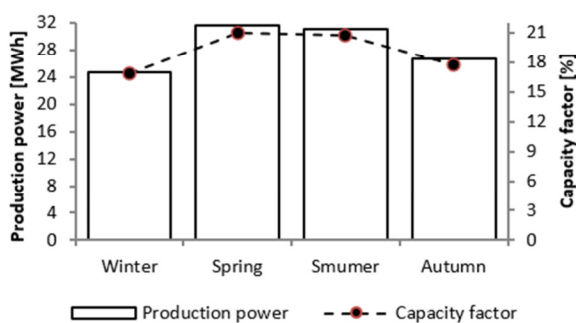


Fig. 9. Estimated LCOE value for the developed system.

F. Emission Reduction

Besides the economic viability, it would be interesting to calculate the ecological benefits of constructing the proposed system in terms of the tons of GHG emissions that would be prevented. The total annual reduction in CO₂ emissions in the chosen case study is displayed in Figure 10. According to the results, implementing the proposed PV project in the chosen area can prevent a sizable quantity of CO₂.

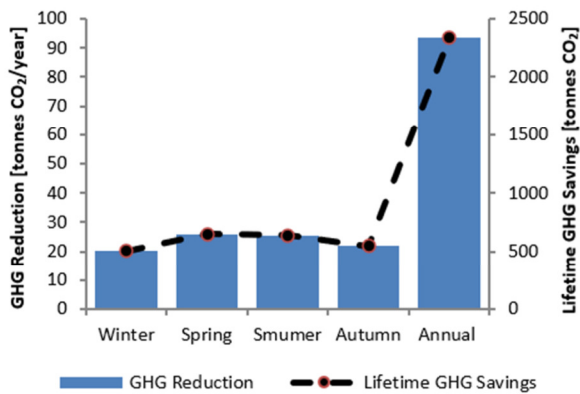


Fig. 10. The estimated GHG reduction and lifetime GHG savings for different seasons.

G. Energy Savings and Profit Calculation

This section assesses the financial and operational advantages that the PV system provides. According to the survey, the total energy demand for accommodation for the workers is about 15kWh/day (i.e., 1380 kWh/season). Figure 11 illustrates the Energy Needs for the Greenhouse (ENGH), Energy Needs for Accommodation (ENA), Energy Production (EP) by the solar system, and the Energy Saving (ES) from the proposed system.

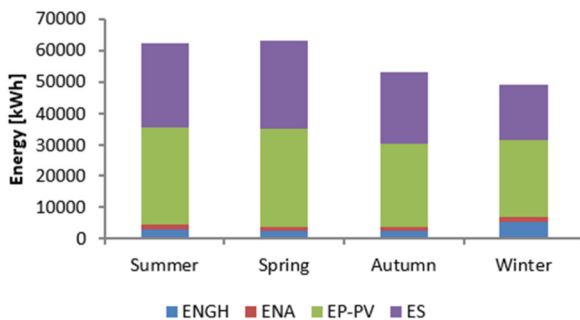


Fig. 11. Energy production and energy saving.

Seasonal variations in electricity demand are observed in the greenhouse operations, with summer and winter presenting greater demands than autumn and spring. Seasonally, the PV system provides most of the energy output; production peaks in spring at 31601.1 kWh and falls in winter at 24685.4 kWh. The results indicate energy savings when the 1380 kWh of energy required for accommodation is deducted: the most significant excess would be in spring (27821.1 kWh), while the lowest would be in winter (17805.4 kWh). This indicates that there is a particular quantity of excess energy accessible. For farmers considering the solar PV systems, the annual profit and cumulative profit are crucial metrics for demonstrating the system's long-term economic viability and benefits. Besides, this analysis reveals the farmer's overall return over the system's lifetime, in addition to the annual savings they will receive a return from the lower reliance on grid electricity. The annual profit is a representation of the savings or earnings from the power produced by the PV system each year. The energy

used to power the farm's greenhouse and lodging requirements is taken into consideration, along with any extra energy that may be sold or used to power other uses, according to the system's LCOE. This annual summary is essential for projecting and organizing the energy-related costs. Besides, the cumulative profit shows the total amount of money made over time after subtracting the initial investment. It helps determine the project's financial viability and long-term profitability. Figure 12 presents the annual and cumulative profit over the system's operational lifetime.

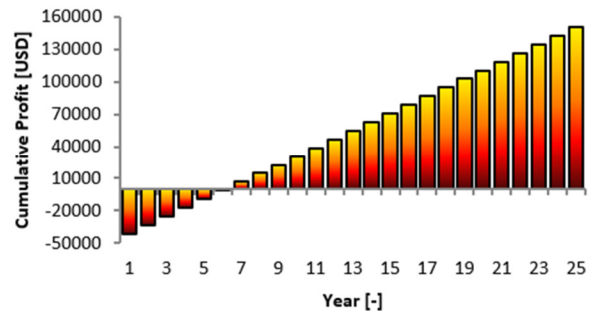


Fig. 12. Energy production and energy saving.

IV. CONCLUSIONS

This study evaluated the solar and wind energy potential in Az-Zāwiyah, Libya, examined the feasibility of implementing an agrivoltaic system, and analyzed the economic sustainability of the greenhouse farming in the region. The core objective was to explore how integrating the solar technology with the greenhouse agriculture could optimize the energy use, reduce the operational costs, and increase the profitability. The findings confirm that while the area's WPD is low and categorized as poor, its SR levels are classified as "Superb", making it highly favorable for PV installations. The proposed agrivoltaic system demonstrated strong performance, especially during spring and summer, generating 31.6 MWh and 31.1 MWh of energy, respectively. The corresponding capacity factors reached 21.05% and 20.72%, indicating a solid energy yield during the peak seasons. The system's SPP is approximately seven years, and the average LCOE is estimated at 7.02 cents/kWh, highlighting its financial viability. Additionally, the energy produced can significantly offset the electricity expenses for the greenhouse operations, contributing to higher profitability. For the system to remain economically feasible, the price of electricity should be around 0.065 \$/kWh. Overall, the results illustrate that the agrivoltaic systems can play a vital role in enhancing the economic and operational sustainability of greenhouse farming in Libya, supporting long-term agricultural resilience and energy independence.

V. LIMITATIONS AND FUTURE WORK

While this study provides valuable insights into the integration of renewable energy in Libya's agricultural sector, it also has several limitations. First, the research is based on a single case study farm in Az-Zāwiyah and may not fully represent the diversity of the farming practices, soil conditions, and climate variations across the country. Additionally, the

analysis relies on modeled and survey data rather than real-time operational data from an existing agrivoltaic system, which limits the accuracy of its findings. The technical and economic evaluations are based on assumptions that could shift with the changing market conditions or environmental factors. Moreover, social and policy-related aspects, such as farmers' willingness to adopt new technologies and the availability of government support, were not thoroughly explored. To strengthen future research, a more comprehensive cost-benefit and policy analysis is proposed. Field testing through pilot agrivoltaic projects across multiple farms would provide more reliable data and broader applicability. Engaging stakeholders and examining the use of renewable energy in water treatment systems would also help expand the study's relevance and scope. Although the proposed system is grid-connected, the integration of energy storage, while costly, was not a focus of this study. Future work should consider the role of the storage technologies in off-grid or hybrid systems to enhance the energy autonomy and reliability. Expanding the study to include multiple farms, real-world testing, and deeper analysis of policy and infrastructure support will improve the reliability and impact of future findings. Additionally, evaluating renewable-powered water treatment solutions and incorporating stakeholder perspectives will further enhance the study's practical value. Figure 13 illustrates a potential hybrid system that warrants further investigation.

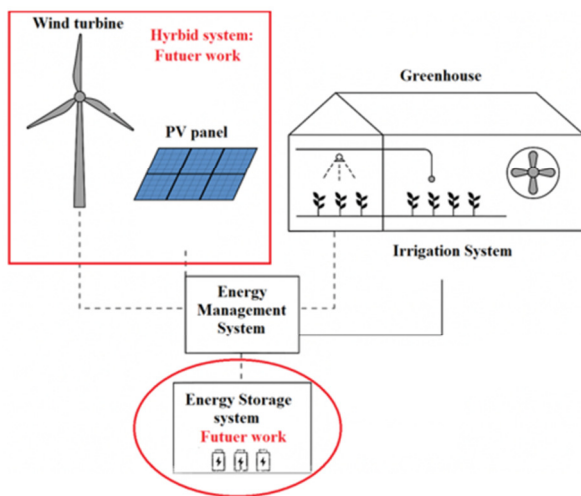


Fig. 13. A prospective hybrid system that requires further investigation.

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