

Innovative Solar-Wind powered Aquaculture System: A Sustainable Solution for Aquaculture in Karbala, Iraq

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ABSTRACT

The primary objective of this study is to present the Solar-Wind Powered Aquaculture Cooling and Energy System (SWPACES), which is capable of reducing Greenhouse Gas (GHG) emissions and the related negative environmental effects, while also reducing water evaporation. The SWPACES combines renewable energy (wind and solar) generation with sustainable aquaculture practices to generate vital power for aquaculture processes. The Husseiniyah River in Karbala, Iraq was selected as a case study. To this end, the MERRA-2 dataset, a reanalysis dataset provided by NASA, was utilized to analyze the wind and solar energy potential of the location. The results indicate that the chosen site has a higher solar energy potential than wind energy potential. Moreover, the economic viability analysis was assessed using the Net Present Value (NPV), payback period, Capacity Factor (CF), and Levelized Cost of Energy (LCOE) under various scenarios (Case I- (Hybrid) and Case II (PV)). The findings demonstrated positive NPV values across several sites, confirming the project's financial viability. Aquaculture farms could afford the project because the payback times ranged from 10 to 12 years, depending on the system architecture. The combined solar-wind system CF ranged from 16.90% to 17.82%. Additionally, the LCOE figures show that SWPACES are affordable, as they are comparable to the existing renewable energy systems. Consequently, the integration of SWPACES not only enhances aquaculture sustainability, but also contributes to the attainment of the United Nations Sustainable Development Goals (SDGs), particularly those concerning responsible consumption and affordable clean energy.

Keywords-Iraq; aquaculture; hybrid renewable energy; Husseiniyah river; sustainable development goals

I. INTRODUCTION

An estimated one-third of the world's anthropogenic GHG emissions originate from food systems [1, 2], which rely heavily on energy, especially fossil fuels, for their productivity [2, 3]. Hence, it is possible to meet national and international climate goals by lowering emissions from the food and

agricultural sectors [4, 5]. Changing the food and energy industries to a reasonable and sustainable approach and preserving food security is challenging [6]. According to [7], utilizing renewable energy instead of fossil fuels is one of the most promising ways to mitigate climate change and increase the sustainability of the food system. Globally, 178 million

metric tons of aquatic plants and animals were produced in 2020 according to the Food and Agriculture Organization of the United Nations (FAO) [8]. Around equal amounts of the world's production come from capture fisheries and aquaculture, or aquatic farming, each of which has different energy needs. According to [4], 179 million tons of CO₂-equivalent GHGs were produced in 2011 by capture fisheries, which primarily employed energy to power vessels and consumed about 40 billion liters of fuel worldwide. In 2017, aquaculture accounted for 245 million tons of GHG emissions owing to energy consumption during grow-out periods and the production of inputs, such as feed and hatchery [9]. Moreover, authors in [10, 11] concluded that the development of the fishing industry's escalating energy costs and related carbon footprint affects both the production process and the supply chain's downstream phases, such as processing, distribution, and retail. Along with decarbonizing the electrical grid, onsite renewables are being explored as a way to reduce dependency on fossil fuels [12, 13].

Iraq is a historic and resource-rich country in the Middle East. However, Iraq's electrical condition has been a continuous issue for decades due to the combination of frequent power outages, inadequate infrastructure, and a reliance on imports to meet energy demands. Moreover, supplying reliable electricity is a challenge for the national grid due to aged power plants, inefficient distribution systems, and corruption in the energy sector. The situation is significantly worse in rural areas, where many industrial and agricultural operations are impacted by power outages and energy availability is limited. The expansion of several sectors, including aquaculture and fish farming, which rely on reliable power sources for aeration, water circulation, and temperature control, is particularly affected by energy crises. Thus, implementing renewable energy sources would help reduce the nation's use of fossil fuels and may be a clean way to generate electricity. The country has a huge solar energy potential compared to wind energy, as reported in several previous studies [14].

Fish farming has become a vital industry in Iraq due to the loss of natural fish stocks in rivers and lakes and the rising demand for seafood [15]. The survival of the industry depends on the country's freshwater resources and many farmers utilize aquaculture to ensure food security and economic prosperity. The Al-Husseiniyah River in Karbala is a key water source for agriculture and fisheries in the area and is one of the most significant locations for fish farming in Iraq. However, several issues, such as water pollution, water shortages, high price of fish feed, fish diseases, and lack of access to modern fish farming techniques, hinder the development of fish farming in the region. Although the government has made efforts to support the aquaculture industry, more rules and infrastructure investments are needed to ensure its long-term viability. The Al-Husseiniyah River fish farming industry may significantly boost regional food security and economic growth in Iraq if the country improves its electrical infrastructure, provides financial support to fish farmers, and implements stricter environmental regulations to protect water quality.

Accordingly, by incorporating sustainable aquaculture practices with renewable energy sources, the project aims to explore the innovative SWPACES in Karbala, particularly along the Al-Husseiniyah River. A new system is proposed that combines solar photovoltaics with various bifacial gains (0, 5%, and 10%) and wind energy that can power essential aquaculture processes, such as water cooling, aeration, and pumping, while lowering GHG emissions and the associated detrimental environmental effects. Furthermore, the patentability of the system as a novel, energy-efficient, and aquaculture-specific solution was evaluated. This research highlights SWPACES' potential for commercialization as a patented idea by analyzing the innovation's energy output, environmental benefits, and financial viability. This research explores the potential for patenting this novel method, which could transform the energy use of aquaculture.

II. MATERIAL AND METHODS

A. Study Area

The Alhusseiniyah area, located along the River Alhusseiniyah in Karbala, Iraq, as depicted in Figure 1, is significant from social, historical, agricultural, and environmental perspectives. The river system sustains local livelihoods through agriculture and fish farming. The area also faces numerous challenges due to climate variability, environmental degradation, and the ongoing poor supply of electricity that influence water management and other economic activities. In general, fish farming is an important aspect of livelihood in the area, since it provides food security and employment opportunities for community members. Common farmed species include carp, tilapia, and catfish. These fish require stable water conditions for optimal growth. However, declining water levels, pollution, and fluctuating temperatures threaten fish health and their productivity. Poor management practices and agricultural run-off with pesticides and fertilizers deteriorate water quality, resulting in reduced production and economic losses.

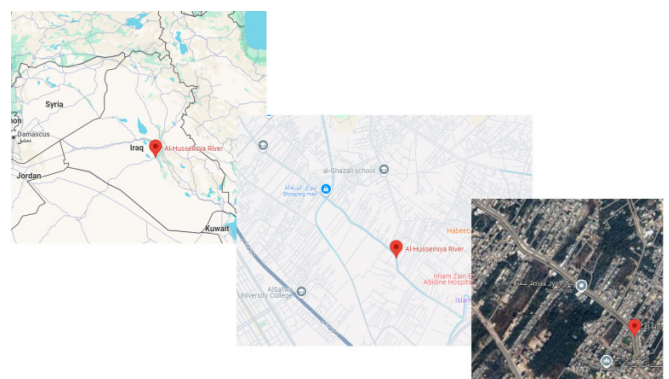


Fig. 1. Location map.

Alhusseiniyah has an arid to semi-arid climate, characterized by hot summers and mild winters. Summer temperatures can reach above 45 °C, whereas winter temperatures generally fall within 5-15 °C. The area is characterized by low annual rainfall, usually not exceeding 150

mm, with rainfall occurring mainly between November and March. Additionally, the evaporation rates are high and there are long dry periods. Therefore, water scarcity affects the agricultural and fishery production. Furthermore, seasonal variations in temperature and water lead to problems in maintaining the quality of the water required for fish farming. One of the major issues in this location is energy shortage, which affects fish farming in the region. Fish farms have aeration systems, water pumps, and temperature control mechanisms that are required to maintain an optimal environment. Power shortages are often experienced, which leads to the failure of such systems, resulting in the depletion of oxygen in bodies of water, eventual deaths of fish, and economic losses for farmers. Alternative energy solutions, such as diesel generators, would increase operational costs, making fish farming unprofitable. In addition, the electricity crisis has affected the infrastructure of water management, irrigation systems, and wastewater treatment facilities. This ultimately reduces the electricity supply, therefore restricting the control of water levels through rivers while aggravating the problems of pollution and the state of the ecological health of rivers.

B. Description of the Proposed System

Figure 2 shows the innovative SWPACES concept that combines sustainable aquaculture practices with renewable energy generation.



Fig. 2. SWPACES concept.

The SWPACES offers a cutting-edge and sustainable solution that integrates solar and wind energy with high-efficiency fish farming. Energy production and aquaculture-related farming are the two interlinked themes addressed by this system. The SWPACES comprises an aquaculture box with eight solar panels, as illustrated in Table I, and one wind turbine, as displayed in Table II, placed on its roof to enhance energy generation. It should be noted that the Vertical Axis Wind Turbine (VAWT) has replaced the Horizontal Axis Wind Turbine (HAWT) because of its lower cut-in speed and ease of maintenance [16]. VAWTs are commonly selected in areas with variable wind directions and lower wind speeds because

of their typically lower cut-in speeds compared to HAWTs [17]. VAWTs are generally easier to repair because of their lower operating altitude and simpler structure. Additionally, their use can reduce operating costs, particularly in remote areas [18]. The structure was 6 m long, 4.5 m wide, and 3.5 m high, with the elevation above the water surface being influenced by the river flow. The optimal orientation and tilt angle for solar PV systems were estimated using the RETScreen software [19].

TABLE I. SPECIFICATION OF SELECTED SOLAR PANEL (CS3W-445MB-AG)

Variable	Bifacial gain		
	0%	5%	10%
Nominal max. power [W]	445	467	490
Opt. operating voltage [V]	40.9	40.9	40.9
Opt. operating current [A]	10.89	11.43	11.98
Open circuit voltage [V]	48.9	48.9	48.9
Short circuit current [A]	11.54	12.12	12.69
Module efficiency [%]	19.9	20.9	21.9
Frame area [m ²]	2.234	2.234	2.234
Cost [USD/W]	0.40	0.50	0.55

TABLE II. SPECIFICATION OF SUNSURF WT3 VERTICAL AXIS WIND TURBINE

Variable	Value
Rated power [kW]	50
Startup wind speed [m/s]	1.8
Rated wind speed [m/s]	10
Survival wind speed [m/s]	28
Rated rotating speed [rpm]	40
Diameter [m]	18
Tower height [m]	14

Corrosion-resistant galvanized iron was used to build a fish-farming cage. The cage, which can hold 100 to 150 fish per cubic meter, provides an environmentally benign, high-density alternative for fish breeding. Water circulation is maintained by a plastic net surrounding the cage, which protects the fish from external threats. This is crucial for the fish health. The solar panels' shading effect lowers water evaporation and maintains oxygen levels by regulating water temperature. Moreover, to complement solar energy, a wind turbine is installed to ensure continuous electricity generation, particularly at night or during periods of low sunlight. This system provides stable and reliable power supply options to reduce the dependency on fossil fuels and mitigate the impact of electrical power shortages in the region. The solar-wind energy system supplies power to the aeration, cooling, and circulation systems, maintaining optimal conditions for fish farming. This system addresses the SDGs, particularly SDG 7 (Affordable and Clean Energy), SDG 14 (Life Below Water), and SDG 2 (Zero Hunger). In addition, this system helps reduce GHG emissions, enhance biodiversity, and create opportunities for local economic development. The SWPACES system is designed to be implemented worldwide, as it provides a self-sufficient and environmentally viable approach to address energy shortages, food security, and water resource management in different aquatic settings.

C. Wind Energy Assessment

Understanding the wind characteristics is essential for evaluating the viability and potential of wind energy of a given area. Therefore, the characteristics of wind speed and wind energy potential were estimated using the Weibull distribution function. The Weibull distribution function is a useful tool for determining the amount of electricity produced by a specific wind turbine [20]. This is represented by the probability distribution function (1) and the cumulative distribution function (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 in m/s and k and c are the shape and scale parameters, respectively.

Several techniques have been employed to determine the Weibull parameters. In this study, the Maximum Likelihood Method (MLM) was deployed [21]. The k is estimated using numerical iterations in MLM by:

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

Numerical iterations were carried out using (3) and an assumed initial k until the previous iteration's k value was sufficiently close to the current k value. Once the k is determined, then the known value of k can be used to find the 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.

The mean wind speed \bar{v} can be estimated using the Weibull parameters as:

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

Furthermore, one of the most crucial measures of wind potential for wind farm design is the Wind Power Density (WPD) [22]. WPD was used to evaluate the potential of wind resources at the specific site and was calculated by:

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

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 was utilized to describe the wind energy potential at the specific location as follows: poor (WPD $\leq 100 \text{ W/m}^2$), marginal (WPD $\leq 150 \text{ W/m}^2$), moderate (WPD $\leq 200 \text{ W/m}^2$), good (WPD $\leq 250 \text{ W/m}^2$), and excellent (WPD $\leq 300 \text{ W/m}^2$).

In general, wind speed data were gathered at a standard height of 10 m above ground level. A power law model was implemented to estimate the wind speed at various hub heights. This model is defined by [23]:

$$\frac{v}{v_{10}} = \left(\frac{z}{z_{10}}\right)^{\frac{0.37 - 0.088 \ln(v_{10})}{1 - 0.088 \ln(z_{10}/2)}} \quad (7)$$

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} .

D. Solar Energy Assessment

The potential of solar energy was assessed by classifying it according to the yearly levels of Global Solar Radiation (GSR). The GSR is regarded as a crucial metric for evaluating the capacity of photovoltaic systems to generate electricity. Furthermore, solar energy potential was categorized according to the annual value of GSR [23] as follows: poor (annual GSR $< 1191.8 \text{ kWh/m}^2$), marginal ($1191.8 < \text{annual GSR} < 1419.7 \text{ kWh/m}^2$), fair ($1419.7 < \text{annual GSR} < 1641.8 \text{ kWh/m}^2$), good ($1641.8 < \text{annual GSR} < 1843.8 \text{ kWh/m}^2$), excellent ($1843.8 < \text{annual GSR} < 2035.9 \text{ kWh/m}^2$), outstanding ($2035.9 < \text{annual GSR} < 2221.8 \text{ kWh/m}^2$), and superb (annual GSR $< 2221.8 \text{ kWh/m}^2$).

E. Evaporation Estimation and Annual Water-Saving

Several methods for calculating the evaporation of water from free surfaces have been reported in literature [24]. The Penman-Monteith method was employed to calculate the evaporation rate (E). This can be expressed as [24]:

$$E = \frac{0.047 \cdot \Delta \cdot R_n + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 U_2)} \quad (8)$$

$$e_s = \frac{1}{2} \cdot \left[0.6108 \cdot \exp\left(\frac{17.27 T_{max}}{T_{max} + 237.3}\right) + 0.6108 \cdot \exp\left(\frac{17.27 T_{min}}{T_{min} + 237.3}\right) \right] \quad (9)$$

$$e_a = \frac{RH}{100} \cdot e_s \quad (10)$$

where R_n is the net radiation [W/m^2], U_2 is the wind speed at 2 m height [m/s], Δ is the slope of saturated vapor pressure–air temperature curve [$\text{kPa}/^\circ\text{C}$], γ is the psychrometric constant (depends on temperature and atmospheric pressure) [$\text{Pa } ^\circ\text{C}^{-1}$], e_s is the saturated vapor pressure at the temperature of the air [kPa], e_a is the vapor pressure at the temperature and relative humidity of the air, and RH is the relative humidity [%].

Moreover, the Water Savings (WS) from installing the proposed system can be determined using [24]:

$$WS = E_{monthly} \times A \times 0.70 \quad (11)$$

where $E_{monthly}$ is the monthly evaporation, A is the box's surface area that prevents water evaporation [m^2], which is equal to 27 m^2 .

F. Simulation Tool for Economic Viability

Numerous simulation software packages, such as RETScreen, can be employed to evaluate the performance of renewable power systems [24]. The RETScreen was created by Natural Resources Canada to assess the risks, costs, economic viability, carbon reduction, energy production, and savings of

different renewable energy sources [19]. Meteorological data from the MERRA-2 NASA dataset [25] were gathered using RETScreen. Utilizing this technique, the evaluation of how a renewable energy system reduces its environmental impact can be completed quickly and efficiently. RETScreen software was deployed to assess the techno-economic viability of the proposed system.

III. RESULTS

A. Results of Wind Energy Assessment

In this study, wind speed data for the selected locations were collected between 2010 and 2022. Figure 3 presents the descriptive statistics of the data. The average wind speed was 3.95 m/s, fluctuating between 3.88 and 4.07 m/s. With an average of 3.95 m/s, the mean wind speeds were determined to be between 3.88 and 4.07 m/s. Moreover, the standard deviation values, which fell between 0.45 and 0.83, were comparatively small.

As previously mentioned, the Weibull distribution function was utilized to analyze the characteristics of the wind speed data. The annual values of the Weibull parameters are shown in Figure 4. The MLM approach was employed to determine the values of k and c . According to the results, the annual values of k and c fall between 4.94 and 8.27, and 4.09 and 4.41 m/s, respectively. The highest recorded value of c was in 2013, and the lowest was in 2010. Moreover, Figure 5 illustrates the Weibull probability plots and frequency histograms of the chosen location's wind speed.

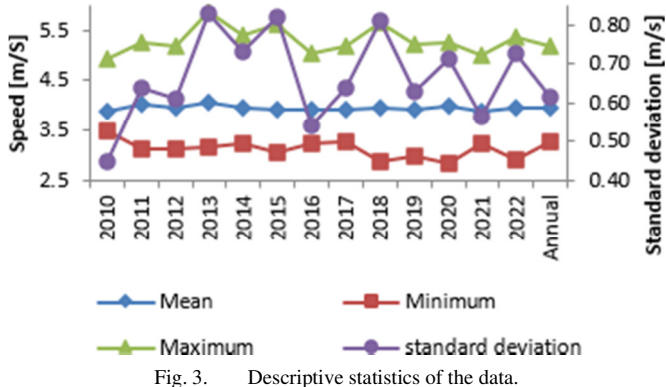


Fig. 3. Descriptive statistics of the data.



Fig. 4. Annual Weibull parameters (k and c).

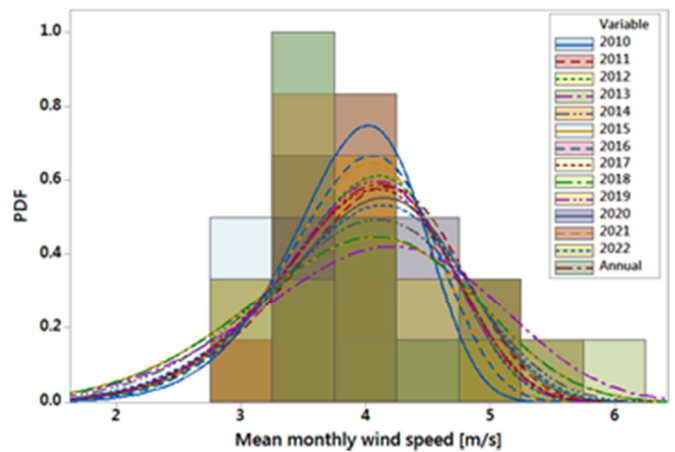


Fig. 5. Frequency histograms and PDF plots of wind speed.

Figure 6 portrays the mean and WPD, which were computed using (5) and (6), respectively. According to the data, the highest and lowest values were 4.04 m/s and 3.86 m/s in 2013 and 2010, respectively. Moreover, the WPD values were found to have an average of 41.03 W/m^2 and fluctuated between 37.21 and 46.81 W/m^2 . According to the WPD values, the chosen site has a comparatively low wind energy potential and is classified as of power class 1 (poor ($WPD \leq 100 W/m^2$)). Therefore, the best strategy for efficiently utilizing the existing wind energy resources in these areas is to install small-scale wind turbines.



Fig. 6. The annual values of the mean and WPD were calculated using the Weibull parameters.

B. Results of Solar Energy Assessment

The mean monthly variations in Solar Radiation (SR) at the selected locations are displayed in Figure 7. The SR values ranged from 76.88 kWh/m^2 (December 2019) to 247.69 kWh/m^2 (July 2020), according to the findings. Additionally, the results demonstrated that the highest annual value of SR, 236.27 kWh/m^2 , was recorded in June, whereas the lowest value, 89.30 kWh/m^2 , was reported in December. As previously mentioned, the solar energy potential can be categorized based on the annual SR value. The estimated annual SR value is 1980 kWh/m^2 , indicating that the location is classified as Excellent ($1843.8 < \text{Annual GSR} < 2035.9 kWh/m^2$).

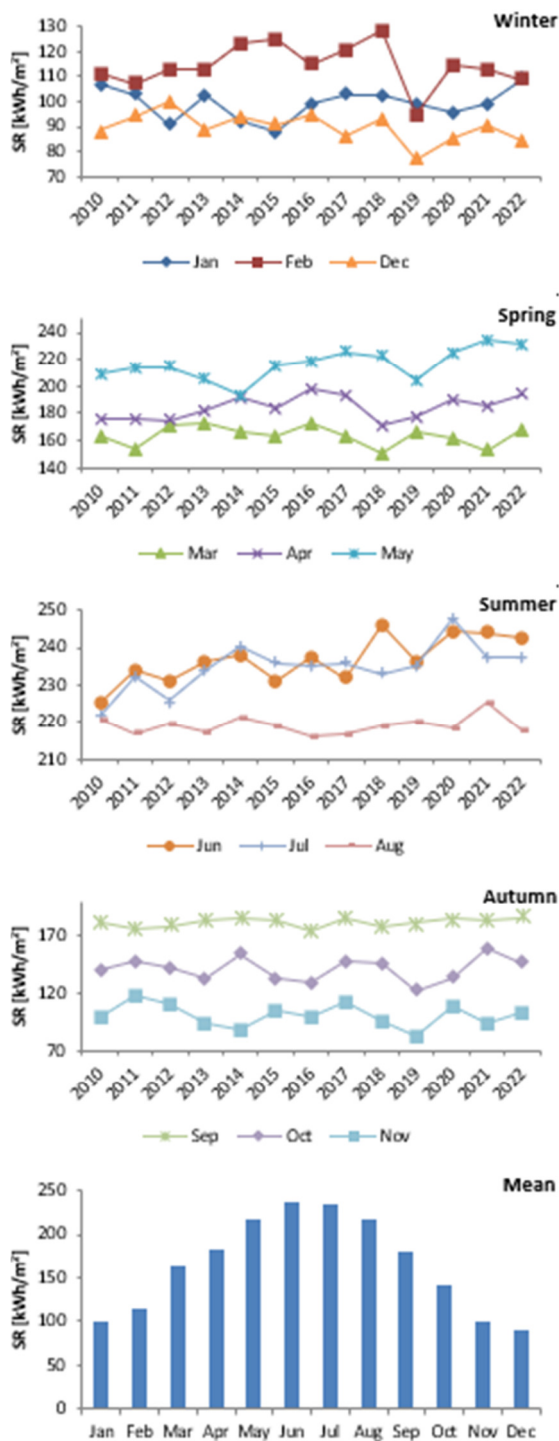


Fig. 7. Monthly and seasonal values of SR during the period of 2010-2022.

C. Results of Evaporation and Annual Water-Saving

In this study, the mean monthly variation in Evaporation (*E*) was calculated using mean monthly weather data, including temperature, solar radiation, wind speed, and relative humidity. The average monthly and seasonal variance in *E* for the chosen site is shown in Figure 8.

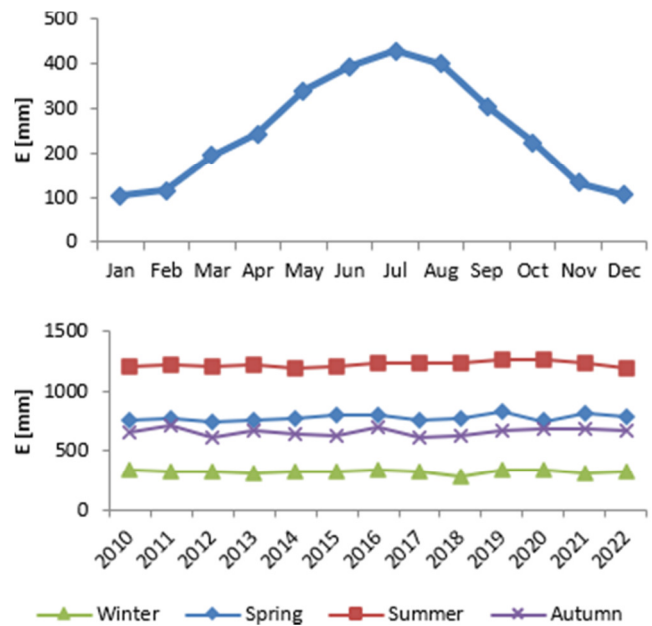


Fig. 8. Monthly and seasonal variance of *E* during the period 2010-2022.

Warmer months have higher evaporation rates, whereas cooler months have the lowest *E* rates. The lowest value of *E* (103 mm) was recorded in January, and the highest value (428 mm) was recorded in July. In addition, the annual rate of *E* is estimated to be 2980 mm. This suggests that if evaporation exceeds the average annual rainfall, there can be a water deficit, which has important implications for hydrological studies, agriculture, and water resource management. Understanding these trends is essential for sustainable projects and effective planning, particularly in regions with limited water supplies. As mentioned before, the goal of the current work is to develop a SWPACES designed to produce 1 MW of power. Hence, various scenarios of the river's covered area were examined as follows:

- Case I: The system consists of eight solar panels with varying bifacial gains and a wind turbine. There are approximately 19 boxes in total, covering 513 m² of space. Notably, 18.67 boxes were required for a 0% bifacial gain and 18.61 boxes for a 5% bifacial gain. When the bifacial gain increased to 10%, the required number of boxes decreased to 18.55.
- Case II: The system consists of eight solar panels with various bifacial gains. The number of boxes required is determined by the bifacial gain because higher bifacial gains result in reduced box requirements and increased energy efficiency. In particular, 281 boxes were required for 0% bifacial gain (Case I-1) and 268 boxes for 5% bifacial gain (Case II-2). When the bifacial gain is raised to 10%, the required number of boxes decreases to 255 (Case II-3). As presented in Figure 9, for the baseline scenario, "one box and no renewable energy system" only 56.32 m³ of water was saved. With 19 boxes and a 54-kW system, the "Case I" design dramatically boosted WS to 1069.99 m³/year, exhibiting the positive effects of incorporating renewable energy systems on water conservation.

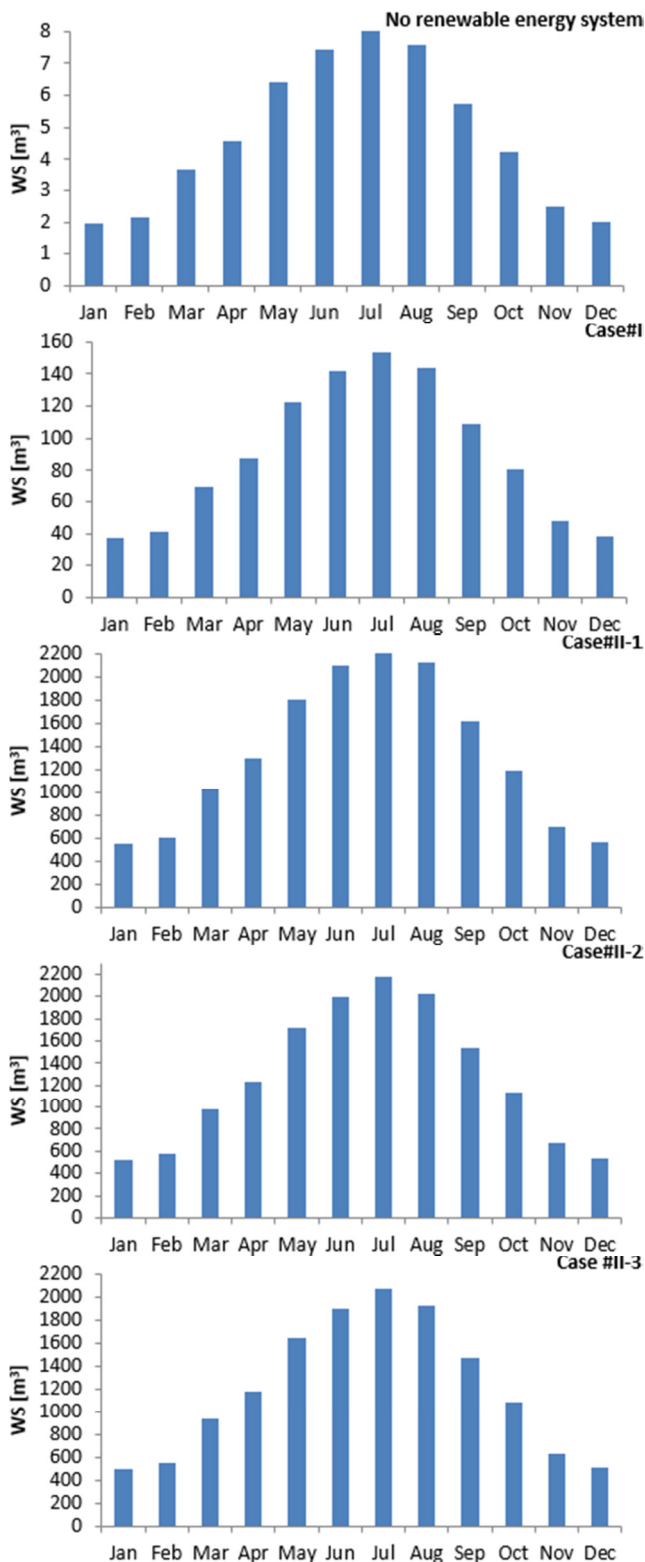


Fig. 9. Monthly value of SR during the period of 2010-2022.

For fish farmers, particularly in areas where water resources frequently fluctuate, this translates to improved sustainability and consistent water supply. Combining solar and wind energy

increases the system's dependability and extends its benefits to both daytime and nighttime operations, boosting overall efficiency and preserving resources. With 281 boxes and a 3.56 kW system, "Case II-1" achieves the maximum WS of 15,824.59 m³/year, highlighting the configuration's notable benefits for both energy generation and water conservation. In addition, there are significant WS of 15,092.49 m³/yr and 14,360.39 m³/yr with "Case II-2" and "Case II-3" with 268 boxes of 3.74 kW and 255 boxes of 3.92 kW, respectively. This is especially important for fish farmers who operate in water-scarce areas since it ensures a more consistent supply of water and reduces operating costs. The nation's broader environmental and economic goals are supported by these water conservation initiatives. They help alleviate pressure on the nation's water resources. Given that they ease the burden on traditional water delivery infrastructure, promote sustainable farming practices, and support national water conservation measures, they can help the country become more resilient to water scarcity and support the SDGs.

D. Results of Economic Viability

Since the same box can be placed in a river, farm, or the sea based on the needs of the site, these systems are adaptable. Therefore, the techno-economic analysis evaluates the performance and economic viability of the renewable energy systems in different configurations for Case#I (54 kW), Case#II-1 (3.56 kW), Case#II-2 (3.74 kW), and Case#II-3 (3.92 kW). The techno-economic analysis of the project in Iraq was based on the following assumptions: inflation rate (3.1%), discount rate (5.5%), reinvestment rate (9%), fuel cost escalation (2%), debt ratio (44%), debt interest rate (7%), and debt term (20 years). The cost breakdown included engineering costs of 2%, installation costs of 6%, transportation costs of 2%, electrical connection costs of 7%, miscellaneous costs of 1%, and civil work. Under different bifacial gain levels (0%, 5%, and 10%), Figure 10 and Table III display the CF and the Electricity Exported to the Grid (EEG) for two different system configurations: Case I (solar-wind hybrid system) and Case II (solar system). At 10% bifacial gain, Case I produced the most power exported to the grid annually (106,567 kWh), whereas at 0% bifacial gain, the least amount of power (105,659 kWh) was produced. In Case II, the lowest quantity of exported power was 4,296 kWh at 0%, and the highest amount was 5,203 kWh with a 10% bifacial gain. Moreover, the CF in Case I peaked at 17.82% when the bifacial gain was 10% and reached its lowest point at 16.90% when there was no bifacial gain. In addition, the CF varied from 13.78% at 0% to the highest value of 15.15% at 10% bifacial gain in Case II. These results indicate that integrating PV with wind energy offers superior power generation and efficiency compared with a standalone PV system. This approach enhances a country's energy security, grid stability, and export potential through improved performance from bifacial gains. A more reliable and cost-effective power supply is provided to fish farms by combining solar and wind energy, which is crucial for running machinery, like pumps and aeration systems. Additionally, bifacial PV panels optimize energy output, especially in reflecting environments, making this choice beneficial for sustainable aquaculture methods.

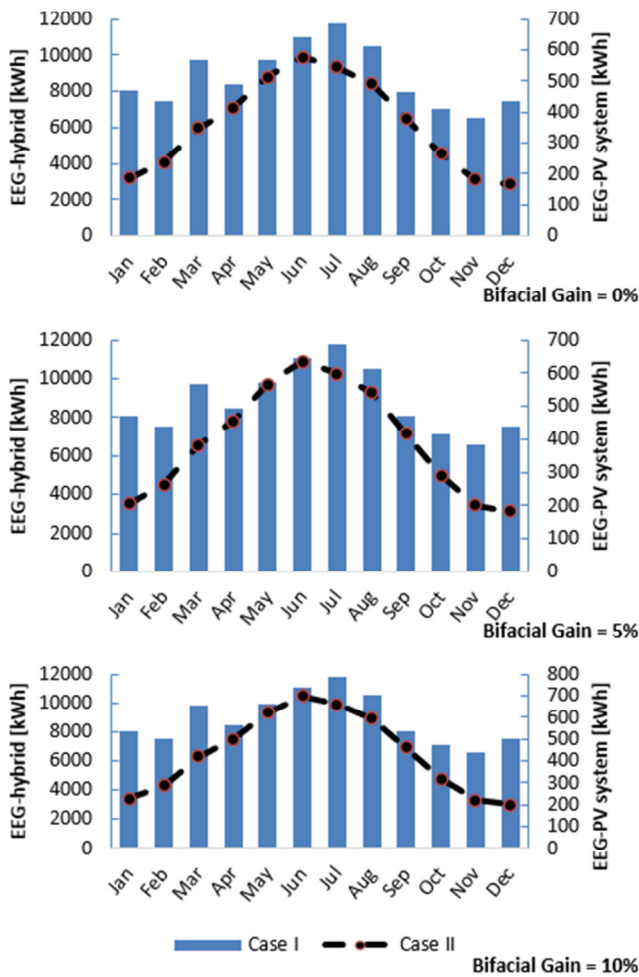


Fig. 10. Monthly value of annual EEG for cases I and II.

TABLE III. SPECIFICATION OF SUNSURFS WT3 VERTICAL AXIS WIND TURBINE

Bifacial gain level	Case I- (Hybrid)	Case II (PV)
Annual EEG in kWh		
Bifacial gain = 0%	105659	4296
Bifacial gain = 5%	106097	4734
Bifacial gain = 10%	106567	5203
CF in %		
Bifacial gain = 0%	16.90	13.78
Bifacial gain = 5%	17.36	14.46
Bifacial gain = 10%	17.82	15.15

Table IV displays several financial and environmental variables for each bifacial gain scenario (0%, 5%, and 10%). It is found that the reduction of gross annual GHG emissions is slightly increased with a higher bifacial gain. In Case I, 110.01 tons of CO₂ (0% gain) increased to 110.96 tons (10% gain). Case II showed a lower loss, from 4.66 tons (0% increase) to 5.65 tons (10% gain). Moreover, in Case I, the simple payback period remained relatively consistent between 12.25 years (0% gain) and 12.15 years (10% gain). Besides, the payback period is shorter, beginning at 10.21 years (0% gain) and declining slightly to 10.20 years (10% gain) in case II.

Moreover, with a bifacial gain, the NPV increases in all scenarios: Case I attains a 10% gain of \$70,448.06, while Case II reaches \$2,981.74. Furthermore, annual life cycle savings, which range from \$5,139.52 (0%) to \$5,251.86 (10%) in Case I and from \$182.87 (0%) to \$222.29 (10%) in Case II, improve slightly with bifacial growth. Additionally, both cases maintain the benefit-cost ratio constant, with Case II staying at 2.80 for all gains and Case I increasing from 1.95 (0%) to 1.97 (10%). In addition, Case I's energy production cost is lower, starting at \$0.0751/kWh (a 0% rise) and then slightly decreasing to \$0.0745/kWh (10% gain). Case II has a 10% rise at \$0.0828/kWh and a 0% gain at \$0.0830/kWh, respectively.

TABLE IV. SPECIFICATION OF SUNSURFS WT3 VERTICAL AXIS WIND TURBINE

Variable	Bifacial gain 0%		Bifacial gain 5%		Bifacial gain 10%	
	Case I	Case II	Case I	Case II	Case I	Case II
Gross annual GHG emission reduction [tCO ₂ /year]	110.01	4.66	110.47	5.29	110.96	5.65
Simple payback [Years]	12.25	10.21	12.20	10.19	12.15	10.20
Equity payback [Years]	8.28	7.41	8.24	7.37	8.20	7.39
NPV [\$]	68941.24	2453.05	69668.20	2796.28	70448.06	2981.74
Annual life cycle savings [\$]	5139.52	182.87	5193.72	208.46	5251.86	222.29
Benefit-Cost (B-C) ratio	1.95	2.79	1.96	2.80	1.97	2.80
Energy production cost [\$ /kWh]	0.0751	0.0830	0.0748	0.0827	0.0745	0.0828

IV. DISCUSSION

According to the study's findings, SWPACES in Karbala is a feasible economic initiative because it offers both financial and environmental benefits for the following reasons:

- The SWPACES has a positive NPV and manageable payback periods at the selected location, making it economically feasible. The positive NPV, which is the difference between the present value of cash inflows and outflows throughout the project duration, attests to the system's financial sustainability.
- Additionally, the CF value of the current study may be supported by several investigations. According to [26], the CF values for 50 m hub-height turbines ranged from 31.1% to 49%, whereas those for 75 m hub-height turbines ranged from 37.3% to 56.6%. For a BWT 61 m–800 kW wind turbine, it was found that the simple payback and CF values varied from 1.9 to 27.3 years and 4.5% to 37.2%, respectively [27]. According to [28], the payback period varied from 6.34 to 19.9 years for several 100 MW wind farms. According to [29], the CF values ranged from 32% to 38% for different types of wind turbines. Authors in [30] showed that the CF values for various wind turbines with diverse parameters ranged from 6.8% to 47.6%. In [31], the

proposed annual CF of the PV system ranged from 20.70% to 21.70%. Furthermore, the payback period for the designed PV system varied between 13.6 and 14.6 years. For the constructed PV system, Authors in [32] observed simple payback time values between 6.38 and 7.00 years, and annual CF values between 17.5% and 20.03%. According to [33], a 12.25 kW grid-connected PV system's CF value is 22.

- The study's simple payback term is between 8.2 and 12.25 years, which is in line with payback times reported in [28], which vary from 6.34 to 19.9 years for large wind farms. This indicates a tolerable initial investment recovery period and demonstrates the SWPACES project's long-term financial feasibility. Additionally, equity investors benefit from a relatively short return on investment, as evidenced by payback periods ranging from 7.37 to 8.28 years.
- The energy production costs of the system ranged from 0.0745 to 0.0830 USD/kWh, which is consistent with the findings in [31], where the LCOE values of the PV systems ranged from 0.128 to 0.135 USD/kWh. This displays the cost-effectiveness of the SWPACES system compared to alternative renewable energy sources, as the LCOE estimates for PV systems in various studies ranged from 0.01025 to 0.08703 USD/kWh. Numerous scientific investigations support these findings. For instance, in [27], it was found that a BWT 61m–800 kW wind turbine's LCOE ranged from 0.04 to 0.43 USD. According to [29], the range of the LCOE values was 0.255 USD/kWh to 0.306 USD/kWh. The CF values in [30] ranged from 6.8% to 47.6% for several wind turbines with various features [30]. Authors in [34] reported that the LCOE values for a 5-kW grid-connected PV system ranged from 0.036 USD/kWh to 0.049 USD/kWh, whereas the LCOE values for a 5 kW Vertical Axis Wind Generator-V ranged from 0.08703 USD/kWh to 0.01025 USD/kWh. According to [31], the proposed PV system's LCOE values ranged from 0.128 USD/kWh to 0.135 USD/kWh. In [33], the developed PV system's LCOE value was 0.0382 USD/kWh.

V. CONCLUSIONS

This study presents the Solar-Wind Powered Aquaculture Cooling and Energy System (SWPACES), which provides a sustainable solution for reducing greenhouse gases, minimizing water evaporation, and providing a renewable energy-backed cooling system for aquaculture facilities. The results showed that solar energy has huge potential compared to wind energy at the specified site. Additionally, the results demonstrate that SWPACES is an alternative approach to aquaculture sustainability, which helps achieve the primary objectives of the UN Sustainable Development Goals (SDGs), such as resource conservation and clean energy. This approach promotes the following SDGs: 7 (Affordable and Clean Energy), 13 (Climate Action) by reducing carbon emissions, and 14 (Life Below Water) by promoting sustainable aquaculture practices. This can be accomplished by promoting renewable energy use. Developing a new technology that can be utilized commercially also supports SDG 9 (Industry, Innovation, and Infrastructure), which helps build a sustainable

and scalable model for the aquaculture industry. Consequently, the SWPACES system is not only commercially viable, but also offers cost-effective renewable energy alternatives for aquaculture cooling. The proposed system is ideal for places, such as Karbala because it promotes economic growth, supports environmental sustainability, and is in line with SDGs 7, 13, and 14, the global sustainability goals.

Further research is required for field implementation, real-time performance monitoring, smart energy management system integration, water quality and cooling benefit evaluation, expanding out to new locations, and full-fledged environmental impact assessments to further evaluate and improve the system's performance and reliability.

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