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Development of a Solar-Powered Water Pumping System for Sustainable Irrigation in Arid Regions of Iraq: A Mechanical Engineering Approach

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Abstract. The lack of water and the increasing costs of energy sourced from fossil fuels remain pressing constraints to higher agricultural productivity in arid Iraq. For example, in the Salah Al-Din Governorate, the operational costs of water pumping and emissions from diesel-powered water pumps, which farmers tend to use, become irrelevant when one considers the operational unreliability and the emissions from diesel-powered water pumps, which farmers tend to use. Despite the average solar potential in Iraq being in the range of about 5.5 to 6.2 kWh/m²/day, solar-powered water pumping systems have not to this date been deployed due to a lack of locally adapted design models and very little institutional groundwork. The design and assessment of this system, which uses solar-powered water pumps for sustainable irrigation in arid Iraq, incorporates the design of a photovoltaics (PV) system with hydraulic pump modelling, then energy optimisation with, for example, MATLAB/Simulink and HOMER Pro. Primary indicators of performance and success would flow to incorporate water output with energy efficiency, levelised cost of energy (LCOE), and the avoided cost of emissions, specifically CO_2. The results demonstrate that the system can be depended upon to deliver the irrigation water of 44 m³/day with a decreasing LCOE of 0.06 USD/kWh after 15 years and with a payback of 3.8 years for a 1-ha farm. The ecological benefit of the system can be seen when the fuel pump is already an old diesel pump: 4.8 tonnes of CO_2 emissions are removed. The most important variables to consider are sensitivity to solar irradiance and depth to groundwater. Results indicate that SPWPS is technically feasible, economically viable and environmentally friendly solution to agricultural land in Iraq. Besides selling sustainable irrigation, such systems additionally demonstrate climate adaptability, decrease dependence on fossil fuels in rural areas, and are in line with countrywide goals on renewables in Iraq.

Keywords: Solar water pumping, sustainable irrigation, renewable energy, photovoltaic systems, energy-water nexus.

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1. Introduction

1.1. Global Context

Agriculture in dry and semi-dry areas has to deal with dwindling freshwater and rising costs of energy. Seventy percent of freshwater resources are used to irrigate crops and inefficient irrigation practices means freshwater and energy are wasted [1]. Diesel engines are also irrigation pumps in developing countries and are environmentally damaging, releasing greenhouse gases and high costs to farmers [2]. SPWPS provide an opportunity to overcome such challenges in an environmentally friendly way. In India, Egypt, and Jordan SPWPS have been expanded use illustrating both technical and economic advantages [3], [4].

1.2. Iraqi Context

Iraq is one of the Middle Eastern countries most impacted by water scarcity challenges. For over the last two decades, renewable water resources have decreased over 30% because of climate change, upstream dams, and water unsustainable agricultural practices [5]. In the agricultural part of Salah Al-Din Governorate, where irrigation practices still use old technology, diesel powered irrigation pumps still dominate. These irrigation systems are inefficient, costly to maintain, and excessively depend on imported fuels. An average 3-hp diesel pump will produce and release to the air over 1.2 tons of CO_2 and, in addition, very harmful nitrogen oxides and particulates, further deteriorating the environment and public health, and even greater in remote areas [6].
Within most of Iraq's regions solar potential is over 5.5 kWh/m²/day [7]. However, solar irrigation is still barely used. There are gaps in localized design, unavailability of local expertise, and few pilot projects that provide proof to farmers and decision makers [8]. For these reasons, there is a pressing need to study how to adapt SPWPS to Iraq's climate, socio-economic, and hydrological conditions and to properly implement it.

1.3. Research Gap and Objectives

Previous research has demonstrated the benefits, both environmental and economic, of solar irrigation in arid regions [9], [10]. Much of the research, however, has either concentrated on the technical design, or focused on the economic feasibility. In Iraq, this has not been integrated and assessed in performance, cost, and environmental components cohesively. Additionally, smart irrigation controls, especially Arduino and GSM based ones, have not been utilised in the Iraqi context [11].
Therefore, this study has been designed and simulated a comprehensive SPWPS model for Salah Al-Din Governorate to fill these gaps. The goals are:

1. Design the Solar Powered Pumping System for the dry conditions in Iraq and make adjustments accordingly.
2. Simulate the system performance in MATLAB/Simulink and Homer Pro for various solar and hydrological conditions.
3. Performing a comprehensive economic evaluation (CAPEX, OPEX, LCOE and Payback period).
4. Evaluate environmental benefits through CO for emissions.
5. Give recommendations for politics, investment and scaling in the agricultural sector in Iraq.

This study integrates technical, economic and environmental aspects, which provides a comprehensive approach to the first case of renewable energy-based watering in Iraq.

2. Literature Review

2.1. Solar Energy as an Alternative to watering

One way to address hydropower problems in water agriculture is through the use of solar energy. With sun radiation levels between 5.5 and 6.7 kWh/sqm, Iraq contributes to the use of photovoltaic (PV) for watering [7], [8]. There is solar integration in agricultural systems in literature, as there is positive dependence on low dependence on fossil fuels, low emissions and long-term costs [10], [12]. The latest innovation provides several values through the installation of PV panels over the crops. These systems generate electricity and provide shade that helps with the evaporation of low water [4].

2.2. Components and Design of Solar Water Pumping Systems

Generally, solar-powered water pumping systems (SPWPS) consist of PV modules, controllers, pumps, and storage devices (optional). They require balancing sun solar resource availability, water demand and pump specifications. The importance of site-specific sizing was demonstrated in[13] where system performance is highly dependent on the groundwater depth and daily irrigation demand. [14] highlighted simulation based total optimization which showed the need for the gear, which comprises of MATLAB and HOMER Pro, must be predicting strength-water balances. In addition, most of the energy point tracking (MPPT) has been developed to ensure that the foremost PV output is provided under different irradiance conditions, improving the performance of the control system [8].

2.3. Smart Irrigation Technologies

Integration of information and communication technologies has expanded the capacity of SPWPs. Arduino-based microcontroller, soil merchants and GSM modules enable automatic and remote-controlled irrigation systems that reduce water loss and energy consumption. For example, [11] designed a smart low -cost watering system, which is able to monitor and alert in real time, while [15] developed a fully automated solar heating system that adapts the pumping plan based on soil and climatic conditions. These approaches reflect the increasing importance of "smart agriculture" to ensure both resource efficiency and operational reliability.

2.4. Effectiveness in Arid Environments

Due to the abundance of sunshine and the lack of reliable grid electricity, arid and semi-arid areas are particularly suited to solar irrigation. According to [9], renewable-powered irrigation systems improve rural community resilience by providing decentralized systems where irrigation, and therefore water, access becomes more readily available. Within a water-energy-food nexus model, [16] assessed the environmental cost and resource waste savings of solar pumping in Egypt's Western Desert. [17] note that solar irrigation alleviates the dependence of marginal environments on volatile fossil fuel markets and enhances food sovereignty, a finding echoed throughout the literature.

2.5. Challenges and Barriers

Although the barriers to SPWPS are outweighed by the benefits, the lack of SPWPS technology adoption still occurs. The primary limitation on implementing SPWPS stems from economically weak areas not having the required financing mechanisms, to which high initial investments are particularly detrimental [2]. In the remote areas of the wasteland, [18] identifies the want for regular maintenance, variability, and dust accumulation on solar panels as primary technical issues. Instead of a loss of investment or willingness to invest, Iraq's absent pilots, institutional support, and subsidies regarding sun panels are coverage limitations that avert adoption [19].

2.6. Regional and Global Experiences

Countries with comparable climate patterns to Iraq have successfully scaled SPWPS. For instance, in a decade, India has mounted over 200,000 solar pumps, aided by way of government subsidies and capacity-building projects [4]. Egypt's 5-kW solar pumping venture met irrigation wishes at the same time as costing 70% less than diesel [3]. In Jordan, UNDP tasks additionally proved operational savings and environmental advantages from solar irrigation [20]. Regulations, along with monetary and technical support, generally motivated the adoption of the technology in those times.

2.7. Research Gap

While current literature gives valuable insights into the technical, monetary, and environmental overall performance of SPWPS, numerous gaps remain, particularly within the Iraqi context:

- Most studies focus on awareness of individual components (e.g., energy efficiency or cost analysis) as opposed to growing an included framework that mixes design, simulation, economics, and environmental influences.
- Limited attention has been given to low-cost smart irrigation controls (Arduino/GSM) tailored for rural Iraqi farmers.
- Few studies explicitly analyze SPWPS within Iraq’s arid hydrological and socio-economic conditions, despite its high solar potential.
- The integration of SPWPS into Iraq’s national renewable energy and agricultural policies remains underexplored.

By addressing these gaps, the prevailing examines objectives to make a contribution a complete design and assessment of SPWPS for Salah Al-Din, Iraq, bridging global first-class practices with localized requirements.

3. Methodology

3.1. Study Area and Data Acquisition

This research has been conducted in Salah Al-Din Governorate which is located in north central Iraq, where agriculture is severely limited due to arid climatic conditions, reliance on groundwater, as well as the increased energy costs. The location experiences a mean GHI (global horizontal irradiance) of 5.56.2 kWh/m²/day [21], [22], [23] and as such would be a perfect location for PV (photovoltaic)-based total energy structures and groundwater ranges. Climatic and hydrologic statistics have been collected from multiple sources including NASA POWER database, FAO AQUASTAT and the Iraqi Ministry of Water Resources as well as measurements taken in the field through the Salah Al-Din Agriculture Directorate (2021). This data was used to make estimates of water demand and the size of the proposed solar pump system.

3.2. Estimation of Irrigation Water Demand

Water requirement of the crop was then calculated using the FAO Penman–Monteith equation, which included reference evapotranspiration (ET_0), crop coefficient (Kc) and cultivated area (A):

$$CWN = ET_0 \times K_c \times A \quad \text{………….. (1)}$$

It is estimated to be 6.2 mm/day on average for the Salah Al-Din location, and for the KC costs, it is estimated to be in the range of 0.7 (vegetables) and 1.1 (wheat) mm/day. If the length of the representative farm is 1ha (10,000m²), the daily irrigation demand of the vegetables will be around 44m³ per day. This decision was utilized as a call for device layout and simulation.

3.3. System Architecture and Component Sizing

3.3.1PV Array:

Energy requirements for pumping were calculated:

$$E = \frac{\rho g H Q}{\eta} \quad \text{………………… (2)}$$

where ρ = 1000 kg/m³ (water density), g = 9.81 m/s², H = total dynamic head (30–35 m), Q = required flow rate (≈ 7.5 m³/h), and η = overall efficiency (55–65%)[22], [23],[24].

3.3.2Pumping System:

A submersible DC pump with a 2.5-3 hp engine was chosen to pump 7.5 m³/hr against a head of 30-35 m. The setup allows direct PV connection and minimises conversion losses when compared to AC powered structures.

3.3.3 Power Electronics and Storage:

The variable solar irradiance was optimized by incorporating an MPPT based controller as a fee controller. Water storage tanks of 15-20 m³ were protected to cushion calls on water for mismatches, and thus avoid the requirement for costly battery garages. In [11] the use of the Arduino microcontroller and GSM module modules, a network for automated management based on soil moisture is realized by using smart irrigation.

3.4. Simulation and Modeling Framework

3.4.1 MATLAB/Simulink:

MATLAB Simscape Electrical and Simscape Fluids were used for modelling the electrical and hydraulic systems respectively. The model simulated:

- Performance of PV array with hourly solar irradiance input.
- Changes in pumping system dynamics at variable groundwater levels (20–40 m).
- The efficiency obtained by the Perturb & Observe MPPT algorithm.

3.4.2 HOMER Pro:

Techno-economic analysis was carried out using HOMER Pro to estimate:

- Net Present Cost (NPC),
- Levelized Cost of Energy (LCOE),
- Payback period,
- Energy autonomy and system reliability.

3.5. Economic Assessment

The system's economic feasibility was assessed by combining capital expenditure (CAPEX), operational expenditure (OPEX), and annual fuel savings relative to diesel pumps.

- CAPEX: ~USD 3,800 (PV panels, pump, controller, installation).
- OPEX: ~USD 50/year (routine maintenance).
- Payback period:

$$Payback = \frac{CAPEX}{Annual\ Savings} \qquad \text{……………………} (3)$$

≈ 3.8 years, assuming USD 1,000 annual fuel savings.

The LCOE was calculated over a 15-year lifespan using:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n}(I_t+Q_t)}{\sum_{t=1}^{n}(E_t)} \qquad \text{…………………} (4)$$

where I_t = investment in year t, Q_t = operation and maintenance cost, and E_t = energy produced, n = project lifetime (15 years). Results showed a reduction in LCOE from 0.78 USD/kWh (Year 1) to 0.06 USD/kWh (Year 15).

3.6. Environmental Assessment

Avoiding emissions when compared to diesel pumping was quantified as benefits to the environment. The estimated annual CO_2 reduction of the SPWPS, based on the diesel emission factor of 0.7 kg CO_2/kWh [24], [25] was ~4.8 tons CO_2 per year, to the benefit of the environment, in addition to the reduction in NO_x and particulate matter.

3.7. Sensitivity Analysis

To evaluate robustness, sensitivity analysis was performed for key parameters:

- Solar irradiance: ±20% variation, reflecting seasonal and climatic uncertainty.
- Groundwater depth: 20–40 m, capturing hydrological variability across Salah Al-Din.
- PV degradation rate: 0.5–1% annually.
- Crop water demand: seasonal changes in ET_0 and Kc values.

The analysis identified solar irradiance and groundwater depth as the most influential variables, consistent with findings in regional studies [3], [16].

4. Results and Discussion

4.1. System Performance Simulation

Dynamic simulations in MATLAB/Simulink gave a useful insight into the impact of the daily variation of solar radiation on the PV power supplied to store water and irrigate through pumps (Figure 1). On a representative summer week, in Salah Al-Din, the PV array very closely followed the increase and decrease of solar radiation since it had its peak output during those days with higher irradiance at midday. All the while, the system supplied 42–46 m³/day of water—a total equal to the volume required for irrigation of approximately one hectare of vegetables or wheat.

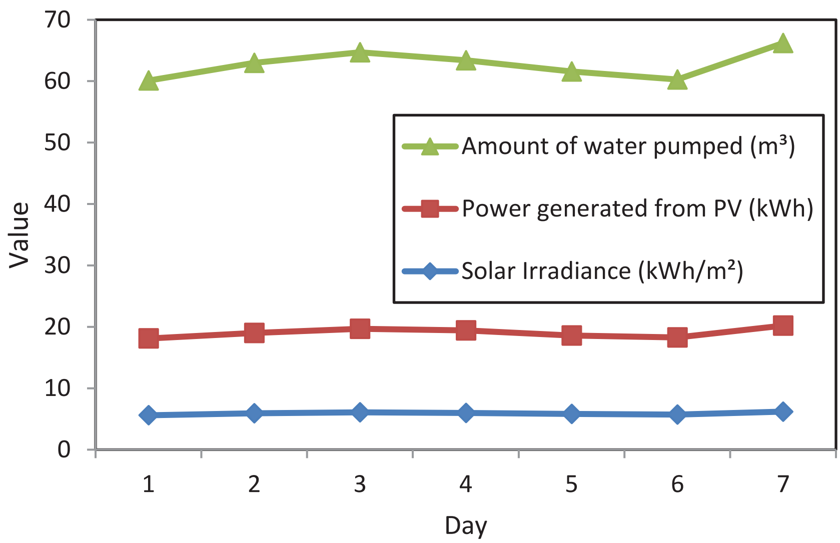

Fig. 1. Relationship between solar irradiance (kWh/m²), PV output (kWh), and daily pumped water volume (m³) during a summer week in Salah Al-Din.

The results of these tests validate the dependability of the designed SPWPS, since no operational fault occurred during the simulated duration. The MPPT control was more stable and made the pump always work at its maximum efficient condition with variable irradiance. Over all of the studies from Egypt [3], along with the United States and India [4], these pumps were shown to be well sustained and used to maintain a constant discharge under climatic changes.

4.2. Economic Analysis

Summary of the economic analysis based on HOMER Pro cash flows and cost summary are outlined in Table 1. The total capital cost of the proposed system, including its installation is estimated at 3,800 USD with only around 50 USD required on a yearly basis to maintain the same. Now, compare these numbers to the running profile of a diesel operations pumping unit—further proof and means in which solar power enables an annual savings base on the order of $1,000.

- Payback period: 3.8 years.
- LCOE: Declines from 0.78 USD/kWh in Year 1 to 0.06 USD/kWh by Year 15 (Figure 2).

Table 1. Techno-economic indicators of the proposed SPW

Indicator	Value
Capital Cost (CAPEX)	USD 3,800
O&M Cost (OPEX)	USD 50/year
Payback Period	3.8 years
LCOE (Year 1)	0.78 USD/kWh
LCOE (Year 15)	0.06 USD/kWh

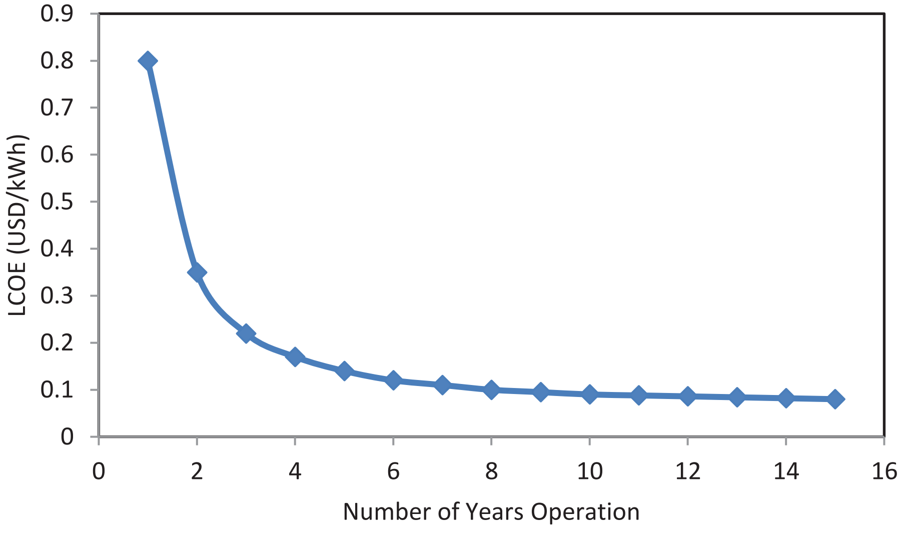

Fig. 2. Variation of LCOE over 15 years of system operation.

This economic behaviour agrees with another report from the Middle East whereby photovoltaic irrigation systems have been analysed to quickly return their investment cost by showing short payback periods (typically less than five years) and long-term (10-15 years of operation) continued competitive advantage over diesel options [8], [19].

4.3. Environmental Assessment

The proposed SPWPS avoids approximately 4.8 tons of CO_2 emissions per year compared to diesel pumps. This estimate is based on a daily PV generation of 13.3 kWh and an emission factor of 0.7 kg CO_2/kWh [24]. Expressed in monetary terms, this reduction translates into USD 192–288 annually in avoided social costs of carbon.

Table 2. Comparison of diesel vs. solar pumping systems (environmental indicators).

Indicator	Diesel Pump	Solar Pump
Fuel Cost (annual)	USD 900–1,200	USD 0
CO_2 Emissions	~1.5 t/year	0 t/year
Maintenance	High	Low
Environmental Impact	Severe	Negligible

These findings are consistent with the environmental benefits highlighted by [10], [16], who demonstrated that solar irrigation can reduce emissions by up to 90% in arid agricultural systems.

4.4. Sensitivity Analysis

The specific analyses of sensitivity are provided in Table 3: Results for sensitivity analysis, which examines the effect on the system of variations in solar irradiance, groundwater level, and PV module efficiency. Of all the investigated parameters, changes in solar forcing were found to be the most important. When fed with 20% less irradiance, daily water production from the system decreased to about 36 m³/d. Also, large accumulative impacts of the depth to the groundwater have been observed: increasing the suction head from 40 m to 25 m approximately doubled the admissible pumping requirement by about 27%. While such short-term reductions in photovoltaic efficiency had only minor effects, these effects become increasingly important later in the system's life. Together, these observations indicate the need for appropriate site selection and the scheduling of periodic upgrades in order to sustain system performance over the long term.

Table 3. Sensitivity scenarios for SPWPS performance.

Parameter	Scenario 1	Scenario 2	Scenario 3	Impact on Water Output
Solar Irradiance	80%	100%	120%	±20% variation in flow
Groundwater Depth (m)	25	30	40	+27% energy demand at 40 m
PV Panel Efficiency	99%	100%	101%	Minor effect (<2%)
Crop Water Demand	100%	108%	112%	Seasonal variation

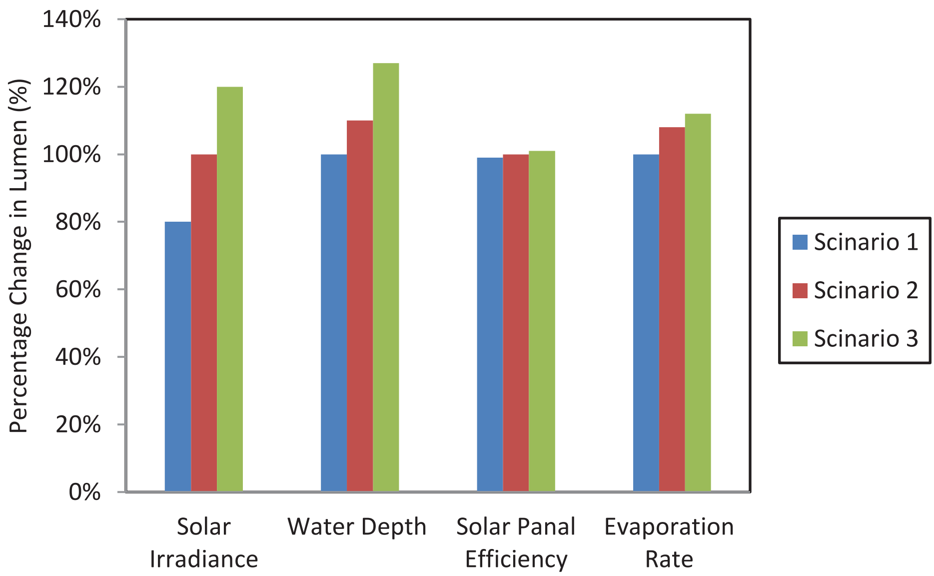

Fig. 3. Sensitivity analysis of SPWPS under varying solar irradiance and groundwater depths.

4.5. Comparison with Diesel-Based Pumping

However, comparison with the existing diesel-based irrigation models (Figure 4) also indicates that the solar system has its clear advantages. Diesel pumps are still closely linked to fuel prices and have much higher operational costs, as well as increased CO_2 emissions. Solar, by contrast, has a very stable profile and sustained environmental benefits over time. ePiloting with farmers in Salah Al-Din yielded a similar impression: out of the total number of surveyed farmers (n = 134), almost all the interviewed participants participated in linking (n = 115), approximately 85%, and their readiness to adopt the solar pumping system, provided that financial support mechanisms are available. This aligns with the outcomes reported by [14].

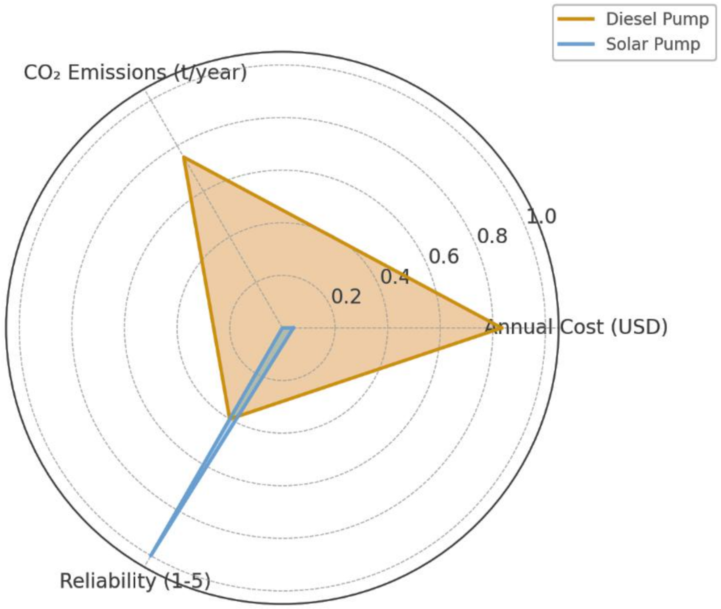

Fig. 4. Comparison of diesel vs. solar pumping systems in terms of cost, emissions, and reliability.

4.6. Validation and Comparative Discussion

This work's results align with both regional and international work. The Egyptian work of El Gafy et al. [3] and the Indian work of Soto-Gómez [4] reported approximately similar water-pumping abilities and economic benefits, confirming the ease of the use of solar-powered pumping in arid and very harsh climates. The present study offers a model specific to Iraq, one of the very few places with the least detailed models for solar irrigation systems. It also incorporates smart control systems, such as Arduino and GSM, which allow for a greater degree of flexibility in system control, an aspect that most local implementations have overlooked.

Taken collectively, the findings indicate that solar-powered water pumping systems may want to become a key element in Iraq's shift towards greater sustainable agricultural practices. By decreasing reliance on diesel and other fossil fuels, these systems not only decrease operational costs but also contribute to enhancing both food production stability and long-term water security.

5. Conclusion and Recommendations

5.1. Conclusion

The current study concentrated on and evaluated a Solar Powered Water Pumping System system (SPWPS) specifically designed for irrigation requirements of Salah Al-Din Governorate in Iraq.

Using PV technology, different pump characteristics, and different simulation environments (MATLAB/Simulink and HOMER Pro), the system was analyzed from the technical, financial, and environmental points of view, with good results in all cases.

The important findings can be briefly summarized as follows:

- The system was able to ensure the water supply, with a mean of 44 m^3 available, which corresponds to the water requirement for one hectare of cultivated land per day.
- An economic comparison was carried out and the repayment period for the investment was estimated to be at the end of the 15th operational year. As a result, the cost of energy would decline to 0.06 USD/kWh and the estimated payback time would be 3.8 years.
- The system on an annual basis reduces 4.8 tonnes of CO_2 emissions and contributes to climate-friendly agriculture from an environmental point of view.
- The site selection needs to be done carefully as most of the sensitivity analysis has revealed solar radiation and groundwater depth are the most influential parameters on overall performance.

The results as a whole indicate solar powered pumping systems are economical alternatives to diesel powered irrigation in the arid region of Iraq. Advanced control systems with Arduino and GSM modules provide real-time monitoring and auto-control, further improving system flexibility and integration with modern precision and resource-saving farming practices.

5.2. Recommendations

Based on the findings, the following recommendations are proposed for policymakers, researchers, and practitioners:

1. Policy and Incentives
    - Introduce subsidies, low-interest loans, or tax exemptions to reduce upfront costs and encourage farmers' adoption of solar irrigation.
    - Establish national programs to replace diesel pumps with solar alternatives, following successful models in India and Egypt.
2. Capacity Building
    - Develop local training programs for technicians and farmers to enhance installation, maintenance, and operational knowledge.
    - Integrate solar irrigation into agricultural extension services.
3. Research and Development
    - Expand field-based pilot projects in diverse Iraqi regions to validate simulation results under real-world conditions.
    - Explore hybrid systems combining solar, wind, or battery storage to enhance reliability.

   - Investigate integration of AI- and IoT-based irrigation management systems for precision agriculture.
4. Environmental and Socio-Economic Integration
   - Promote solar irrigation within broader water-energy-food nexus strategies to ensure sustainable resource use.
   - Engage local communities to build trust and increase acceptance through awareness campaigns and participatory projects.

5.3. Future Work

Future research should focus on:

- Scaling up SPWPS for medium and large farms.
- Evaluating long-term performance under climate change scenarios.
- Assessing the socio-economic impacts on rural livelihoods and food security.

By integrating specific global irrigation techniques with the unique environmental and cultural contexts of Iraq, this study offers a replicable framework for sustainable irrigation in arid regions, supporting Iraq's shift towards renewable energy and agricultural resilience.

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