Optimizing Irrigation with Solar Energy: Implementation of the Photovoltaic Integrated Control System (PICS)

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Abstract: **In Bangladesh, agricultural yields heavily depend on groundwater and traditional irrigation methods, creating dire water scarcity problems and energy inefficiency. The Photovoltaic Integrated Control System (PICS) has been developed as part of this research work to address this issue. As a sustainable irrigation model, the PICS optimizes resource consumption via renewable energy integration and intelligent automation using a quantitative and qualitative approach. The design of PICS is based on photovoltaic panels, Maximum Power Point Tracking (MPPT) technology, and fuzzy logic controllers, which means adjusting directly to weather conditions, soil moisture, temperature, and reservoir levels. Experimental results presented in the paper show that the PICS system saves up to 28.4 percent of water during operation and 53.56 percent in motor power consumption compared with the existing alternatives. These results underscore the potential for the model to aid in resolving groundwater depletion and enhancing energy efficiency. Additionally, integrating solar energy into the PICS enhances sustainability by reducing greenhouse gas emissions. By combining renewable energy with automation, PICS offers farmers an innovative and transformative approach to irrigation, enabling more efficient and environmentally friendly agricultural practices. Its scalability and adaptability across diverse environments, along with its ability to mitigate climate-related challenges and optimize resource utilization, position it as a highly promising solution for advancing agricultural sustainability on a global scale.**

Keywords: **Solar Energy, Irrigation, PICS, Fuzzy Logic Control, Automation, Renewable Energy.**

I. INTRODUCTION

Bangladesh's agriculture, which feeds millions, is facing a sustainability crisis due to inefficient irrigation practices and dwindling groundwater reserves. With 75 percent of irrigation in this country based on groundwater [1], inadequate water management and reliance on fossil fuels threaten the country's agricultural sustainability, food security, and climate resilience. In such regions, the loss of groundwater in irrigation and agro-industrial methods is a frequent issue. In the northwest region, which is especially susceptible to drought, November through May only sees 372 mm of rain, compared to a national average of 546 mm [2,3]. Groundwater resources comprise 75 percent of the total irrigated area. However, excessive withdrawal jeopardizes their long-term sustainability [4].

Because of the two crises of water scarcity and inefficient energy use, Bangladesh's agriculture, which sustains the livelihoods of millions of people, is at a crucial point. In addressing these issues, there is tremendous hope for renewable energy systems, especially solar energy solutions. The adoption of solar photovoltaic (PV) systems leads to a decrease in the emissions of greenhouse gases, an increase in energy resilience, and resource savings, as reliance on diesel-powered irrigation systems is reduced. Despite these advantages, the Energy sector in this country is still heavily reliant on natural gas, which generates 62 percent of electricity; by contrast, only 3 percent comes from renewable energy [5]. To better understand the contribution to renewable energy, the breakdown of the renewable energy sources in this country points to the current energy mix, and the unused hydropower, solar, wind, and other resources are shown in Figure 1. Renewable energy accounted for a mere 3 percent of the national energy supply despite being a focus area for several years, highlighting the necessity for more excellent implementation of sustainable technologies.

The problem of traditional solar-powered irrigation systems arises when motor pumps fail to provide necessary irrigation during adverse weather. While programs like drip irrigation and conventional solar pumps work toward energy and water efficiency, they aren't flexible enough for changing weather patterns, require maintenance involving dirty operations, and don't precisely manage water. For example, drip irrigation systems may be efficient water-use systems. However, they are also heavily reliant on non-biodegradable materials and often lead to soil degradation under heat [6]. These limitations necessitate an advanced, integrated methodology to eliminate such inefficiencies.

The Photovoltaic Integrated Control System (PICS) presented in this paper aims to address these limitations by integrating photovoltaic technology with advanced automation. The PICS, for example, employs fuzzy logic algorithms to modify irrigation parameters dynamically [7], factoring live inputs like soil moisture, temperature, humidity, and water levels, allowing the system to conserve energy and minimize wastage through accurate water distribution. Furthermore, by utilizing Maximum PowerPoint Tracking (MPPT) technology [9], the system maximizes the harvesting energy output from the solar panels, enabling them to work at top efficiency under varying solar irradiance levels. The MPPT algorithm effectively adjusts the PV panels' operating point to maximize energy capture [10].

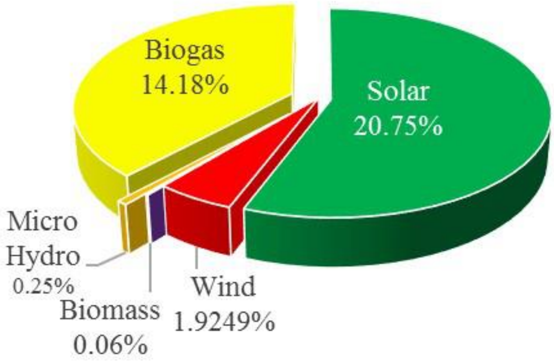

Fig. 1: Current Renewable Energy Scenarios in Bangladesh [8].

Animation-based simulations emphasize potential impact, with 50 to 60 percent water savings and 15 to 25 percent energy reductions, coupled with the immense policy focus on large-scale industrialization and the consequent neglect of rural alternatives, complements the PICS as a flood-restrictive solution for the agricultural sector of Bangladesh. In total, the PICS is different from previous systems in that it combines:

1) Electricity Generation under Solar Dynamic Specifications: The MPPT helps to harvest the most out of energy with fluctuated irradiance along with the role of the battery to ensure operation on unbroken supply [11].
2) Fuzzy Logic-driven Automation: Automated responses based on real-time inputs (e.g., soil moisture, temperature, and reservoir levels) maximize pump efficiency while minimizing water usage, ensuring the system's robustness with no speed overshoot [12].
3) Scalable Cluster: Centralized water storage and sensor networks manage water distribution (water towers, etc.) to each agricultural zone and reduce pressure on regional aquifers and aquifer systems.

Hence, this study aims to design and assess an irrigation system that addresses serious challenges in Bangladesh, such as the depletion of underground water, ineffective utilization of natural resources, and reliance on energy through the proposed system. The program's scalability allows it to be applied to other regions with comparable agricultural issues. The subsequent subsections provide details on the design and implementation of the PICS model, the simulation and experimental results, and the potential for scale in the country's agricultural landscape.

The rest of the paper is organized as follows: section II explains the method of designing and implementing the PICS model; section III presents simulation and experimental results; section IV discusses findings and implications, and section V concludes with recommendations for sustainable irrigation practices.

II. METHODOLOGY

A. Research Framework and Objective

The study aims to design and evaluate a photovoltaic-based sustainable irrigation system incorporating the PICS. The system optimizes water distribution using fuzzy logic algorithms and maximizes energy efficiency with solar energy. This section details the case study, system design, component sizing, and control system modeling.

B. Site Selection

The site selected for the study is in southern Sylhet, Bangladesh (91.8661° E, 24.8918° N) due to its favorable solar irradiance and agricultural importance. The selection criteria included:

1) Topography: Flat terrain for uniform water distribution.
2) Solar Irradiance: Annual average irradiance of 4–6 kWh/m²/day [From the TABLE I].
3) Soil Characteristics: Loamy soil is suitable for irrigation.
4) Water Availability: Proximity to reservoirs and groundwater sources.
5) Climatic Factors: Consistent temperature and sunlight throughout the year.

C. Experimental Setup

An experimental prototype was constructed to validate the system design. A solar panel was connected to an MPPT charge controller with four terminals. The middle terminal of the charge controller was connected to a 12 V battery, which stores energy for continuous operation. A mini boost module was connected to the load terminal of the charge controller, powering a motor driver that drives a DC motor. Parallel to the load terminal, a buck module was installed to supply power to auxiliary components, including an IR proximity sensor, a soil moisture sensor, an Arduino microcontroller, and an LCD monitor, as shown in Figure 2.

The soil moisture sensor was embedded into the soil to be balanced between earth and air; the purpose of embedding them was that by using this sensor, we could measure real-time moisture at the present place. On the other hand, the IR proximity sensor was hooked up to a water container to track reservoir levels. Soil and water moisture outputs were obtained in real time using an LCD monitor, which is very useful for operating the system. An Arduino microcontroller programmed with fuzzy logic algorithms controls the DC motor speed by adjusting the input voltage to the motor driver, enabling fine-grained control of water delivery according to the soil state and the state of the reservoir.

A simple irrigation system was arranged adjacent to the PICS model to compare the water usage. The structure utilized a traditional water direct pump with no automation, which caused the water to flow continuously and be ungoverned. Both systems were measured for their water consumption over a given period. In the traditional method, water consumption was noted manually, which indicated inefficiencies like over-watering and wastage of resources. Subsequent measurements were compared to the PICS system, which based the water flow on real-time soil moisture levels and reservoirs. This comparative analysis demonstrated the advantages of PICS in reducing water consumption and optimizing irrigation practices.

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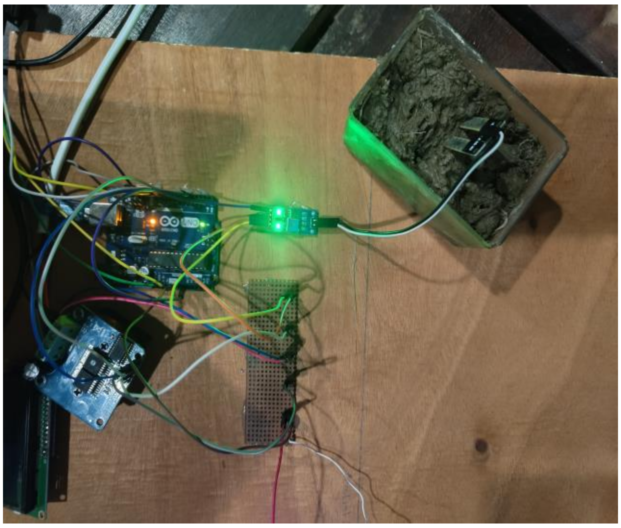


(b)

Fig. 2: (a) Experimental Setup; (b) Sensor Calibration.

D. PICS Schematic Diagram

The schematic diagram is depicted in Fig. 3 indicating all the essential components of the system.

E. Simulation Data

1. Simulation Setup: The performance of the PICS was examined under various conditions via simulations in the MATLAB/Simulink environment. This model included PV arrays, MPPT algorithms, fuzzy logic controllers, and the irrigation motor driver. The simulations assessed how well the system responds to different solar irradiance levels, temperature modifications, and water needs.
2. Solar Panel Specifications: The PV arrays were examined with both constant and variable solar irradiance, and they showed how the MPPT algorithm maintained ample voltage and power output even when sunlight fluctuated. Table I shows the key specifications of the photovoltaic panels used in the PICS design. The parameters were selected for maximum efficiency under local climatic conditions.

TABLE I. SOLAR PANEL SPECIFICATIONS

Model	User-defined
Maximum Power Point	228.7735 W
Voltage	29.9 V
Current	7.65 A
Open Circuit Voltage	37.1 V
Short Circuit Current	8.18 A
Temp. Coefficient of open circuit Voltage	-0.361 %
Temp. Coefficient of short circuit Current	0.102%

3. Solar Irradiance Data Collection: TABLE II shows average horizontal and tilted solar irradiance values in Sylhet, Bangladesh. Data was collected to determine system sizing parameters and optimal PV panel orientation.

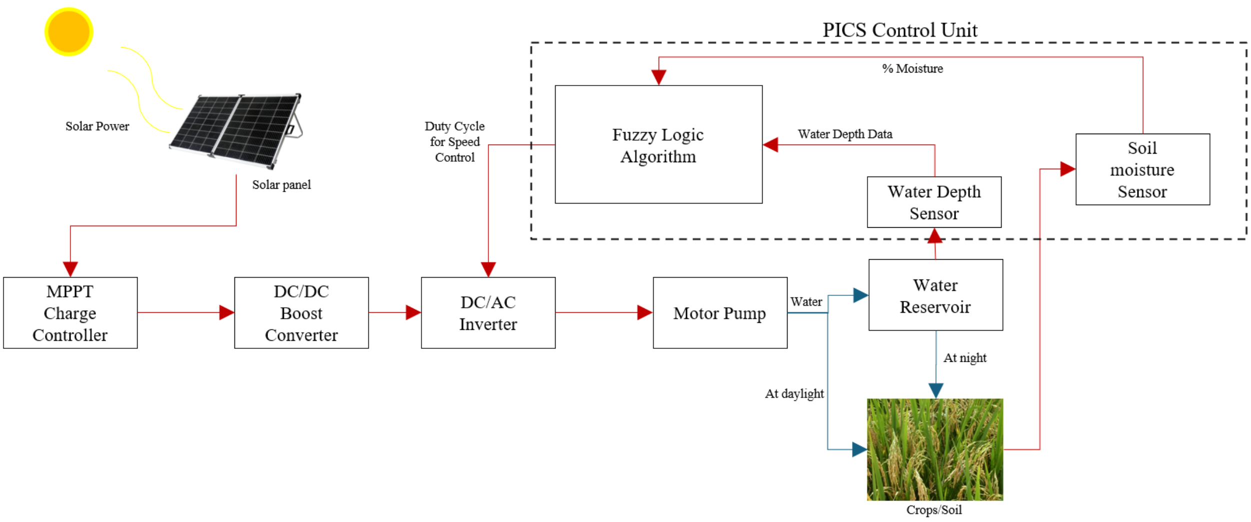


Fig. 3: PICS Schematic Diagram

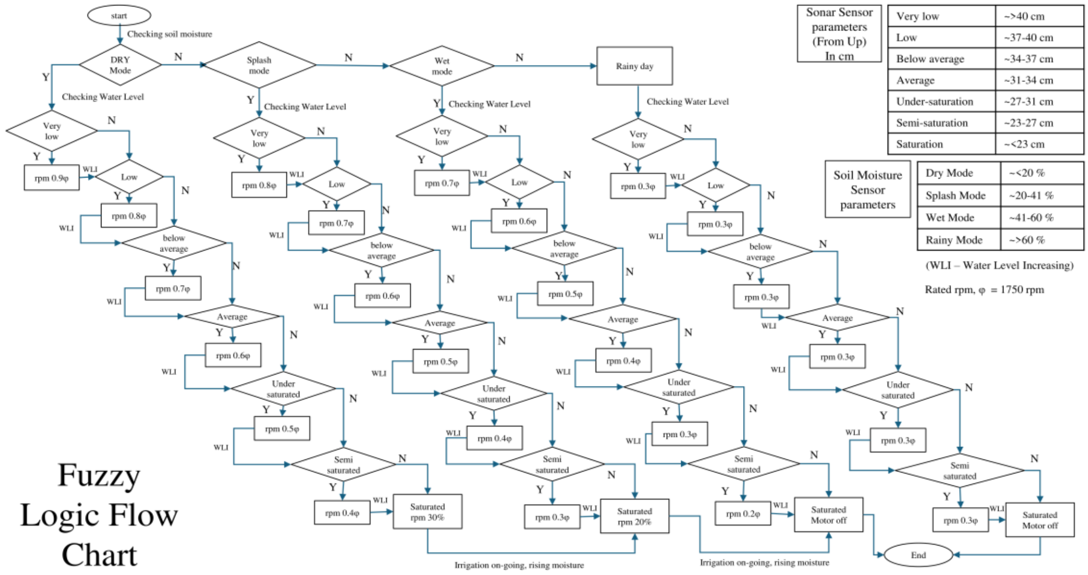


Fig. 4: Fuzzy Logic Flow Chart

4. Fuzzy Flowchart of the PICS Control Unit: The proposed model implements a fuzzy logic hierarchical control structure for intelligent irrigation management. The control architecture featured in Fig. 4 utilizes a multi-tier decision tree processing soil moisture state in unique operational regimes: Dry, Splash, Wet, and Rainy.

   The decision-making process for this system starts with soil moisture conditions and branches according to water level conditions. Each path uses linguistic variables from "very low" to "saturation" to decide needed motor responses. Used control logic with multistage feedback loops allows for improving system performance in case of changing the environmental conditions and deviating irrigation. These parameters must be calibrated before performing according to the PICS installation's environment. The PICS utilizes this advanced architecture to provide accurate water applications by controlling the motor reactively, thereby creating an efficient and responsive irrigation system.

TABLE II. SOLAR IRRADIANCE IN SYLHET DURING 2018-2019 [13]

Month	Horizontal Irradiance	Tilt angle	Avg. Horizontal Irradiance	Avg. Tilt Angle
Nov 2018	4.07	5.2	4.35	4.81
Dec 2018	3.73	4.76		
Jan 2019	4.01	5.24		
Feb 2019	4.48	5.72		
Mar 2019	5.08	4.71		
Apr 2019	4.43	4.91		
May 2019	4.63	4.5		
Jun 2019	4.38	4.02		
Jul 2019	4.02	3.5		
Aug 2019	4.05	4.13		
Sept 2019	4.55	4.68		
Oct 2019	4.76	5.1		

5. Membership functions of Fuzzy Logic Controller: Input membership function for soil moisture and the water depth in the fuzzy logic controller, the ranges (Low, Medium, High) represent degrees of moisture content used to decide irrigation levels and water depth content used to determine the water level. Also, in the fuzzy logic controller's output membership function for percentage RPM, the ranges (Very low, Low, Medium, High, Very high) represent degrees of motor speed used to decide the water flow as shown in Fig. 5.

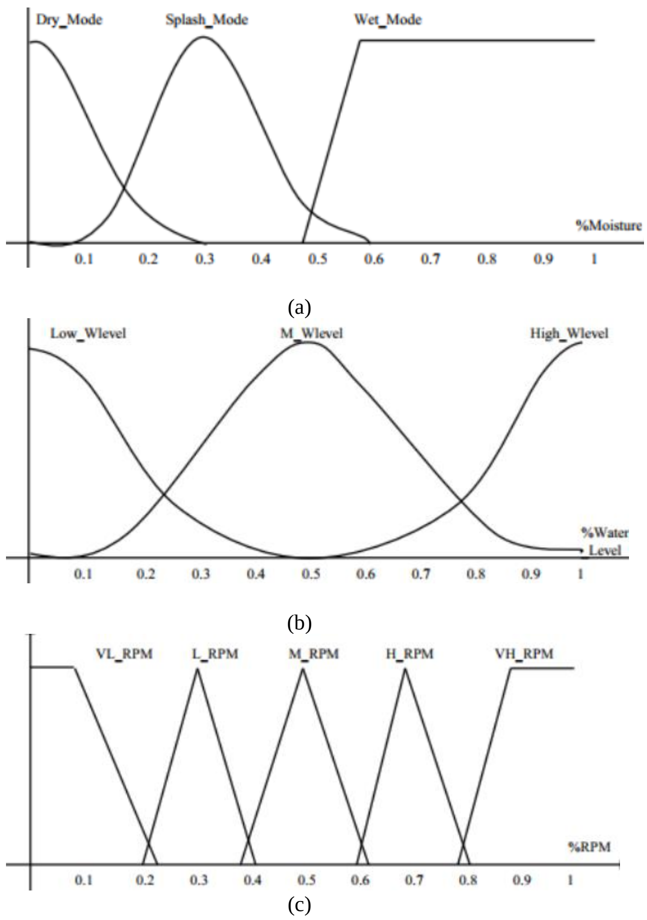
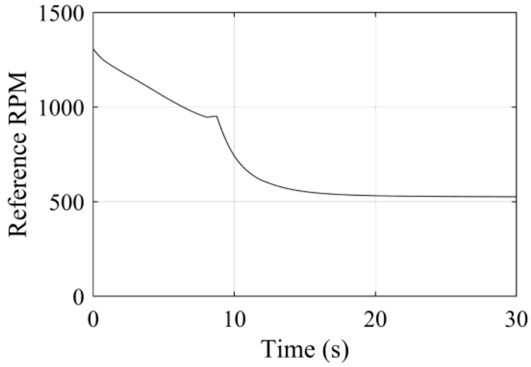


Fig. 5: Membership functions for the Fuzzy logic Controller.

III. RESULTS

A. Simulation Results



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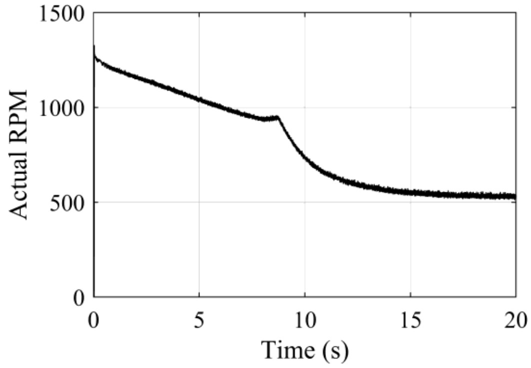

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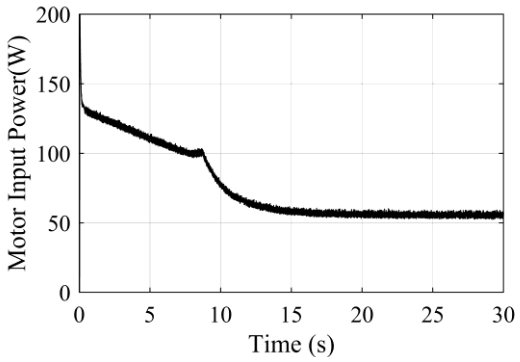

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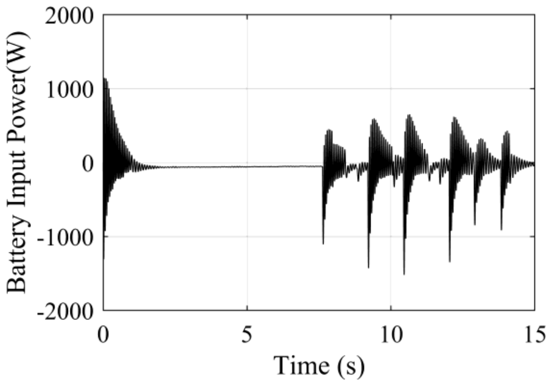

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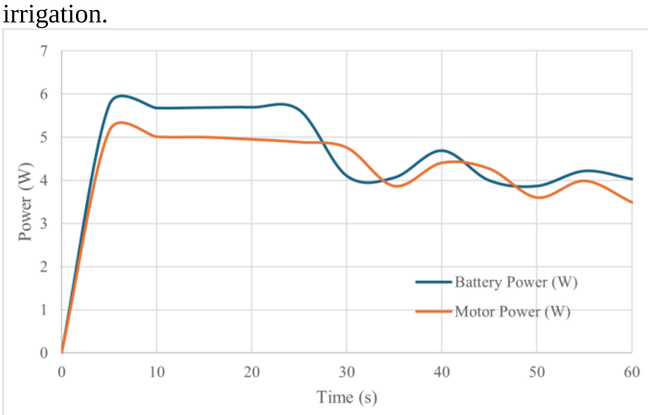
Fig. 6: A comparison graph between (a) Reference RPM and (b) Actual RPM and (c) Motor Input Power and (d) Battery Input Power.

These specialized graphs in Fig. 6 focus on motor performance, power input, and speed. The Actual RPM vs. Time and Reference RPM vs. Time graph shows a slow, smooth decrement in rotation speed that indicates a controlled deceleration. The Battery Input Power vs. Time graph shows spikes. Indeed, the Motor Input Power vs Time graph also has a downward trend similar to that of Motor Input Power, which agrees with the decrease in RPM. Motor speed regulation and power consumption dynamic behavior are reflected in these results, showing that the system has efficiency, performance, and control effects.

B. Experimental Results

The graphs in Fig. 7 illustrate the power, current, and voltage variations over time for irrigation and motor systems. The Battery and Motor Power vs. Time graph shows that battery power remains consistently higher than motor power, indicating energy conversion losses. Similarly, the Battery and Motor Current vs. Time graph reveals that battery current is consistently higher, signifying efficiency losses. Comparing Battery Power for Traditional vs. PICS Irrigation, traditional irrigation consumes more power, suggesting that PICS irrigation is more efficient. The Battery, Boost Converter, and Motor Voltage vs. Time graph demonstrate how boost voltage stabilizes motor operation. Finally, the Motor Power for Traditional vs. PICS Irrigation graph shows that traditional irrigation requires more motor power than PICS, further emphasizing the efficiency of PICS irrigation.



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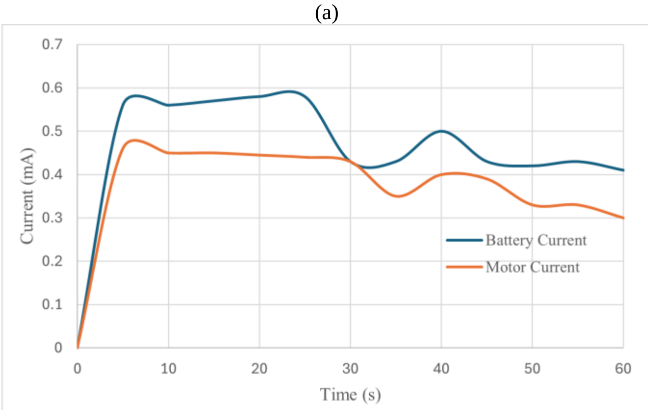

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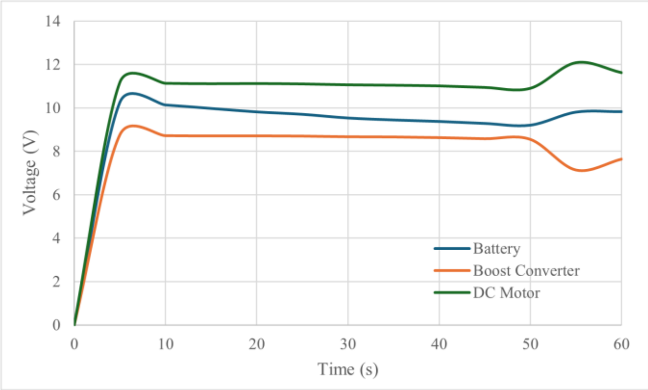

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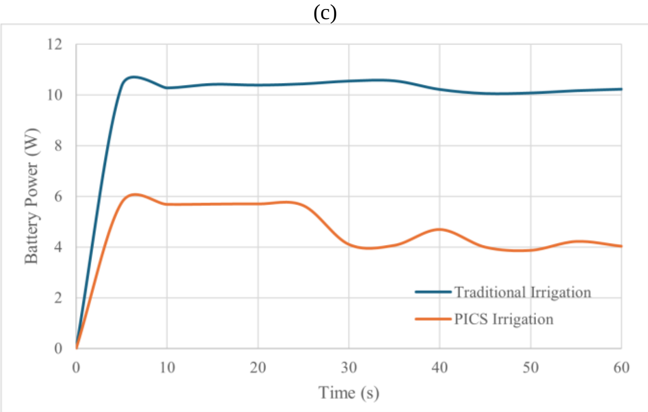

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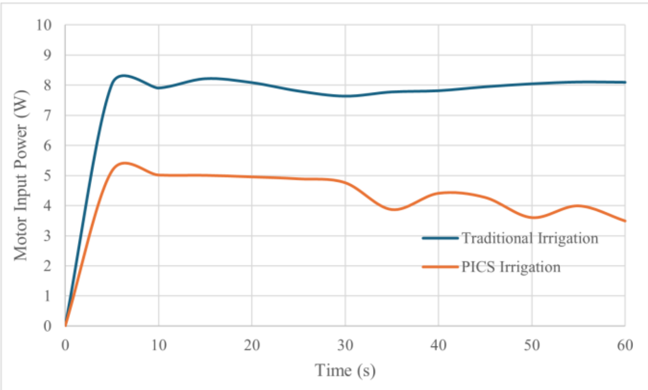

(e)

Fig. 7: Analytical Comparison between Battery and Motor Performance in terms of (a) Power; (b) Current; (c) Voltage vs Time, and Power Comparison between Traditional and PICS Irrigation Process in terms of (d) Battery; and (e) Motor.

IV. DISCUSSION

The PICS significantly advances the integration of renewable energy and smart irrigation. This system uses such real-time inputs to optimize energy and water usage, translating the simulation and experimental data into practice and improving its overall energy efficiency and irrigation regimes. As depicted in Fig. 8 it demonstrates a real and sustainable pathway to meet the challenges of depleting groundwater and poor irrigation systems, with approximately 28.4 percent water savings over traditional irrigation systems.

The core of PICS relies on an advanced fuzzy logic-based control system. This fully automated structure finds the main drawbacks of conventional systems, like nonlinear responses and time delays, and provides accurate water supply according to conditions like soil and reservoir. The MPPT technology used in the system also maintains the energy efficiency of the system design in widely changing solar irradiance. It enables the system to operate consistently throughout changing environmental conditions. This feature is particularly suitable for PICS, especially in places with minor or intermittent power supply.

While these results are promising, several challenges must be solved for broader acceptance. The high installation costs are still a major hindrance, especially for small rural farmers. The operational and maintenance expertise needed to run the system could make it less scalable. Government subsidies, training programs, and public-private partnerships are areas with promise for making PICS more widely available and reducing its cost; you could roll out modular and scalable versions of PICS more easily into various agricultural zones.

Notably, the scalability of PICS has enormous potential for global agriculture. In regions where water scarcity and energy inefficiencies are widespread, PICS can tailor the system to subtle climate differences and include additional features (e.g., predictive analytics) in those import and export facilities that would help overcome similar challenges. The next step would be to improve the system design to make it cost-effective and perform efficiently under extreme environmental conditions.

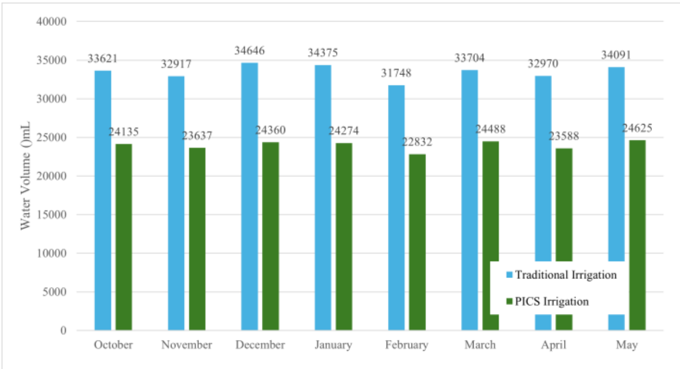

Fig. 8: Water volumetric comparison between traditional and PICS irrigation.

In addition, the findings emphasize the broader significance of incorporating renewable energy into agriculture. PICS considers itself a champion of climate change mitigation and sustainable development by decreasing fossil fuel dependency. The system's conduct on agriculture generates higher productivity and saves greenhouse gas emissions and essential water resources for the environment.

To sum up, the PICS are a revolutionary approach to sustainable irrigation, yet they can achieve their full potential only through innovative development, collaboration, and assistive policies. Overcoming economic and infrastructural barriers will be critical to unlocking this technology's transformative potential in agriculture.

V. CONCLUSION

The PICS is an advanced technology for sustainable irrigation that can improve water and energy efficiency. As explained in the subsection III-B, the PICS saves water by 28.4 percent (Fig. 8) and motor power consumption by 53.56 percent (From Motor Input Power vs. Time graph in Fig. 7). These achievements highlight the device's potential to tackle significant issues, including dwindling groundwater, energy inefficiency, and agricultural sustainability.

Future versions of PICS will incorporate the Supervisory Control and Data Acquisition (SCADA) system as an upgrade to expand its system capacities. This updated feature would optimize extensive irrigation data processing by allowing precise water demand measurement and real-time power usage tracking for comparative tracking purposes. With a SCADA system in operation, the system would track reservoir parameters, including depth and diameter, and environmental inputs while making possible dynamic adjustments to suit regional conditions. Sensors need site-specific climatic and soil characteristic-based calibration, enabling universal operations to perform their best in different agricultural areas.

This integration improves resource utilization in different environments through fuzzy logic-based automation and MPPT technology. PICS are thus a great fit for areas facing power shortages and frequent climate fluctuations.

Although the PICS model holds great potential, widespread adoption has been hindered by technical expertise requirements and steep installation costs. Specific government incentives, public-private partnerships, and farmer training programs will be critical to overcoming these barriers. Future research should also help scale up the system's integrated predictive analytics and lower accessibility costs.

Among these, PICS is the scientific innovation that can change farmers' lives and move our civilization toward sustainable use of renewable energy and intelligent automation. This ability to save precious resources and combat climate change is crucial in improving farmers worldwide. Ongoing innovation and cooperation will help unlock the full potential of PICS, which is suitable for use across different agricultural systems/landscapes.

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