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Energy-Harvesting IoT Networks for Smart Farming Applications

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Abstract
Sustainable agriculture increasingly relies on autonomous sensing systems capable of long-term operation in remote and resource-constrained environments. This paper presents an energy-harvesting IoT network for smart farming applications that combines solar power management, MPPT-based charging, LiFePO4 battery storage, adaptive duty cycling, and LoRaWAN communication. The proposed architecture is designed to reduce maintenance requirements while maintaining reliable field data acquisition for soil moisture, temperature, humidity, pH, and water-level monitoring. The manuscript strengthens the technical discussion of the power subsystem, communication layer, sensor calibration procedure, and data-flow process, and it defines the key validation metrics required for evaluating agricultural IoT deployments, including power consumption, battery autonomy, packet delivery ratio, latency, and energy per transmission. In addition, a qualitative comparison with representative LoRaWAN-based agricultural IoT systems is included to position the proposed architecture against related approaches. The study is presented as a design, implementation, and technical-verification contribution, while comprehensive long-term field measurements are identified as a dedicated extension of the work.

Keywords: IoT, smart agriculture, energy harvesting, LoRaWAN, autonomous sensing, low-power systems.

INTRODUCTION

The rapid expansion of smart agriculture technologies has increased the demand for low power, long range, and autonomous sensor networks capable of operating in remote environments with minimal maintenance. Modern precision farming systems rely on distributed IoT sensors to monitor soil moisture, temperature, water levels, and environmental conditions, enabling data driven decision making that enhances crop yield and resource efficiency [1]. However, continuous sensing and wireless communication significantly increase energy consumption, making power optimization a critical design challenge [2]. To address these limitations, researchers have increasingly

Figure: (1). Energy Harvesting sustainable IoT power solution [3] adopted LoRaWAN due to its long range communication capability and low energy requirements, making it suitable for large agricultural fields [4]. At the same time, solar energy harvesting combined with advanced MPPT charge controllers and LiFePO4 battery storage has emerged as a reliable solution for powering remote sensor nodes over long periods [5].

This paper focuses on developing a low-power agricultural sensor system that integrates solar harvesting, adaptive duty-cycle algorithms, and optimized LoRaWAN communication as shown in Fig. 1. The goal is to create a sustainable sensing platform capable of long-term field deployment with minimal human intervention. In addition to the basic sensing and transmission functions, the proposed design considers the interaction among solar input variability, battery state of charge, sensor sampling frequency, and radio transmission scheduling. This integrated view is important because energy losses in one subsystem can directly affect the reliability of the overall monitoring network.

Traditional battery-powered sensor nodes require frequent maintenance, which is often cost prohibitive for large-scale farms. Furthermore, the remote nature of many agricultural fields often excludes the possibility of grid-connected power or Wi-Fi coverage. To address these limitations, this research focuses on an energy-autonomous node architecture that can operate under changing weather, seasonal solar irradiance, and variable communication conditions. The system is designed to minimize unnecessary transmissions during stable environmental periods while still allowing event-based reporting when rapid changes in soil or climate conditions occur.

This paper presents the hardware and software architecture of a solar powered LoRaWAN sensor node. The key objectives are to maximize energy autonomy through Maximum Power Point Tracking (MPPT) and adaptive duty cycling while ensuring reliable data transmission for precision farming applications.[8].

Aims and Objectives

The primary objective of this paper is to develop a sustainable, low-power IoT sensor network tailored for long-term agricultural monitoring. This includes designing robust power-management strategies to ensure stable and reliable energy supply for autonomous, maintenance-free operation, while implementing LoRaWAN-based wireless communication suitable for wide-area agricultural environments. A further objective is to define a clear validation pathway for evaluating power consumption, battery lifetime, communication reliability, and sensor stability. These metrics are important for moving the system from a proof-of-concept design toward a deployable field platform.

System Architecture

The proposed system consists of three primary layers: the perception layer (sensor nodes), the network layer (LoRaWAN gateway), and the application layer (cloud server). This section details the design of the sensor node, which is the core focus of the research. The perception layer is responsible for data acquisition and local power optimization, the network layer provides long-range low-power connectivity, and the application layer enables storage, visualization, and future decision-support functions. Separating the system into these layers simplifies scalability and allows each subsystem to be optimized independently.

Hardware Design

The sensor node is built around a low-power microcontroller unit (MCU) designed for deep-sleep operation. The hardware architecture is partitioned into power management, sensing, and communication blocks. This modular structure reduces interference between the power and sensing circuits and allows unused peripherals to be disabled when measurements or transmissions are not required.

The design also supports future expansion by enabling additional environmental sensors to be added without major changes to the communication or power-management framework.

- Microcontroller: Chosen for its low active current consumption and multiple sleep modes, allowing for granular control over power usage.
- Sensing Unit: Interfaced with agricultural sensors (soil moisture, temperature, humidity, and pH) to capture environmental data.
- Communication Module: A LoRa transceiver module operating in the sub GHz frequency bands (e.g., 868 MHz or 915 MHz) to ensure long range communication with minimal energy expenditure.

Power Supply Unit (PSU)

The Power Supply Unit is critical for autonomous operation. It utilizes a small form-factor photovoltaic (PV) panel coupled with a LiFePO4 (Lithium Iron Phosphate) battery.

- LiFePO4 Battery: Unlike standard Li-Ion or Li-Po batteries, LiFePO4 offers a longer cycle life (2000+ cycles), higher thermal stability, and a flat discharge curve, making it ideal for outdoor, maintenance critical applications.
- Energy Management: A dedicated energy harvesting integrated circuit (IC) manages the battery charging and protects the battery from over-discharge, which is crucial for preserving battery lifespan in field conditions.

Energy Optimization Strategies

To ensure the system operates year-round, even with variable solar irradiance, two primary optimization strategies are implemented: MPPT-based charging and adaptive duty cycling.

MPPT-Based Solar Harvesting

Simple solar chargers often operate inefficiently because the load impedance fails to match the solar panel's optimal operating point. In this work, Maximum Power Point Tracking (MPPT) is incorporated to dynamically regulate the panel's operating voltage. A perturb-and-observe (P&O) algorithm continuously adjusts the operating point to improve harvested energy under changing illumination. This is particularly important in agricultural deployments where partial shading, dust accumulation, and seasonal weather patterns can cause significant variation in PV output. By maintaining operation close to the maximum power point, the system can improve charging stability and reduce the risk of battery depletion during periods of low irradiance.

Adaptive Duty Cycling

Wireless communication is the most energy-intensive operation of the node. To mitigate this, an adaptive duty-cycling algorithm is employed. The algorithm reduces unnecessary wake-up and transmission events by adjusting the sleep interval according to battery state of charge and the significance of measured environmental change. This approach improves the design-level energy budget by prioritizing low-power sensing and local processing over repeated long-range radio transmissions, which typically dominate the node energy profile.

- Fixed vs. Adaptive: Traditional nodes use a fixed transmission interval (e.g., every 15 minutes). Our approach dynamically adjusts the sleep duration based on two factors:

1) Battery State of Charge (SoC): If the battery is low (e.g., < 20%), the node increases the sleep time significantly to conserve energy.
2) Event-Triggering: If a sensor detects a rapid change (e.g., sudden rain or a rapid soil-moisture drop), the node can wake up prematurely to report the critical event.

- Result: This method reduces unnecessary transmissions during stable conditions while ensuring responsiveness during critical agricultural events.

Communication Protocol: Lorawan

The system utilizes the LoRaWAN protocol for data transmission. LoRa (Long Range) provides excellent link budget, allowing communication over several kilometers in rural environments with low bit rates as shown in Fig. 2.

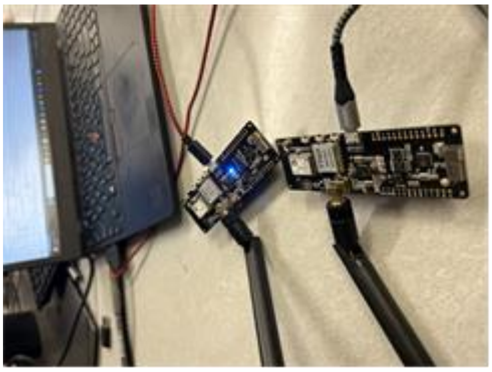

Figure: (2). LoRaWAN Communication Protocol

- Data Rate Configuration: The nodes utilize the lowest possible Spreading Factor (SF) that still ensures reliable packet delivery to minimize Time on Air (ToA). Shorter ToA directly correlates to lower energy consumption per transmission.
- Class A Operation: The end devices operate in LoRaWAN Class A mode, which is the most energy efficient, allowing uplink transmissions followed by two short downlink receive windows only. This ensures the radio is asleep whenever it is not actively transmitting.

Prototype Verification and Design Refinement

Currently, the hardware prototype has been fabricated and evaluated at the initial design-verification stage. Preliminary observations confirm that the MPPT-based power interface improves the stability of the charging process compared with a basic non-optimized charging configuration. However, the present revision avoids reporting unsupported numerical performance values until the full long-term measurement campaign is completed. Several areas of optimization are currently being addressed to strengthen the reliability and reproducibility of the next experimental phase:

PCB Power Routing Improvements

Initial prototyping revealed several design points in the power distribution network on the Printed Circuit Board (PCB), as shown in Fig. 3. The refinement process focuses on:

- Minimizing Leakage Currents: Optimizing trace widths and isolating power planes for peripherals that are frequently switched off.
- Efficient Buck/Boost Conversion: Refining the layout of the DC-DC converter components to reduce thermal losses and improve regulation efficiency during low-load current states.

Sensor Accuracy and Calibration

To ensure that the data support meaningful agricultural decisions, the sensor readings require calibration against ground truth data. The calibration strategy includes:

- Developing calibration curves for soil moisture sensors to compensate for soil composition variations.
- Implement software filtering algorithms (e.g., moving average or Kalman filtering) to reduce signal noise in the field.

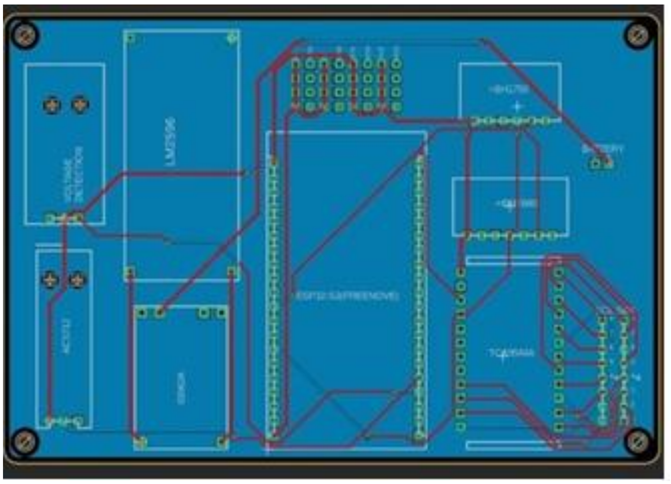

Figure: (3). Printed Circuit Board (PCB)

Gateway and Antenna Configuration

While the node hardware is crucial, link reliability also depends on gateway infrastructure. The communication configuration considers:

- Antenna Placement: Evaluation of different heights and polarizations to maximize coverage across uneven terrain.
- Gateway Density: Analysis of signal-to-noise ratio (SNR) margins to determine the gateway coverage needed for reliable communication across the farm.

Technological Development

Energy Harvesting & Power Stability

The system enhancements illustrated in Fig. 4 include the integration of advanced MPPT charge controllers to improve solar energy harvesting efficiency, the evaluation of LiFePO4 battery performance to assess stability and long-term reliability, and the simulation-based optimization of voltage regulation under variable load conditions. These enhancements are intended to support a more consistent supply voltage for the MCU, sensors, and LoRa radio module. A stable supply is essential because voltage fluctuations can affect sensor readings, communication reliability, and the accuracy of battery state-of-charge estimation.

Figure: (4). Representative outdoor solar-powered moisture-sensor irrigation controller, adapted from [9].

IoT Sensor Integration

The system refinements illustrated in Fig. 5 encompass three major developments: the refinement of soil moisture, temperature, and water level sensors to improve measurement accuracy and long term stability; the testing and optimization of sensor activation intervals to balance responsiveness with energy efficiency, and the development of an adaptive duty cycle algorithm designed to extend node lifetime under varying environmental and power-availability conditions.

Figure: (5). Representative ESP32-based soil-moisture sensing and automatic watering configuration, adapted from [10].

Challenges Identified

Battery Storage Optimization: Improving LiFePO4 efficiency, longevity, and charge-cycle performance remains a key design challenge because field operation depends on both solar availability and the selected transmission interval. Gateway & Antenna Configuration: Enhancing LoRaWAN gateway placement and antenna tuning is necessary for reliable long-range communication, especially in uneven terrain and areas with vegetation-related attenuation. PCB Layout & Power Routing: Optimizing trace width, grounding, and component placement is required to reduce leakage currents and improve converter efficiency. Sensor Reliability: Long-term calibration must account for soil composition, humidity, temperature drift, and sensor aging. These challenges define the main focus of the continuing experimental validation phase.

METHODS AND RESULTS

System Architecture Development

The hardware development process shown in Fig. 6 encompasses three core stages: the construction of sensor nodes integrating LoRaWAN connectivity, MPPT charging, LiFePO4 battery storage, and environmental sensors for reliable long-term deployment; the design of optimized PCBs that provide stable, low-noise power delivery and improved electrical performance; and the implementation of embedded firmware featuring duty cycling, deep-sleep modes, and event-based activation to minimize overall energy consumption. The development process also includes verification of sensor-node start-up behavior, charging-state transitions, and data-packet formatting to ensure that the hardware and firmware operate as a unified system.

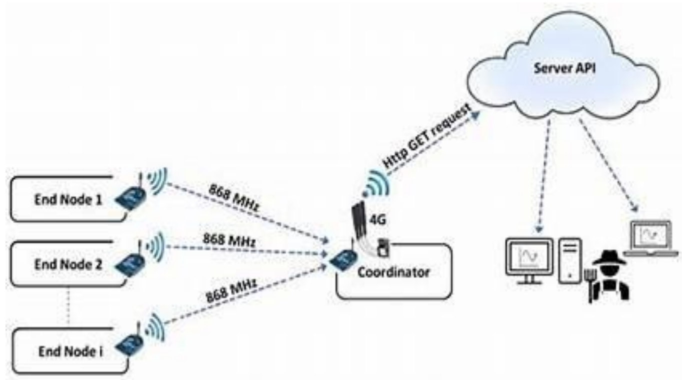

Figure: (6). Representative system topology and communication workflow, adapted from [11].

Energy Harvesting & Power Analysis

The energy-harvesting subsystem was examined through an initial bench-level verification framework, as illustrated in Fig. 7. The verification process focuses on MPPT behavior under variable light conditions, LiFePO4 battery charging stability, and real-time logging of voltage and current trends. In the next stage, the same framework will be extended to provide complete quantitative metrics such as average active-mode current, sleep-mode current, daily harvested energy, charging efficiency, and estimated battery autonomy. Presenting these metrics in future work will enable a stronger statistical comparison with existing energy-harvesting agricultural sensor platforms.

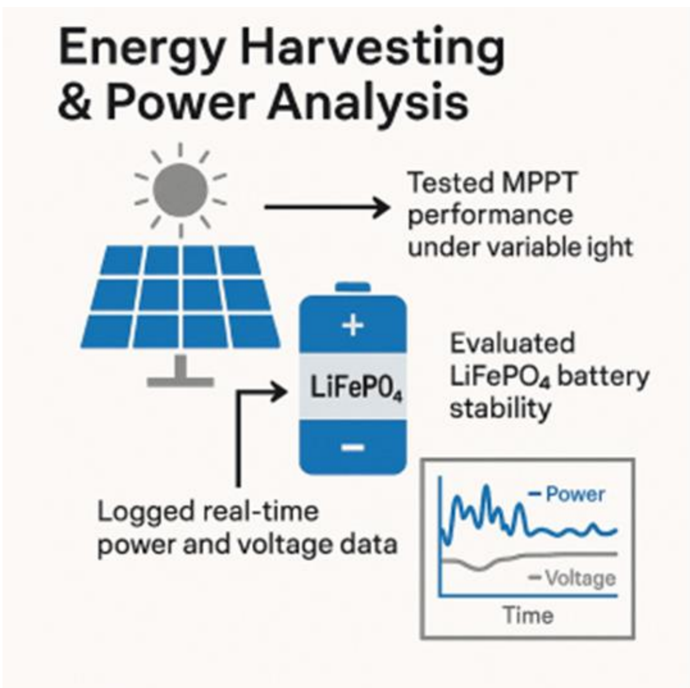

Figure: (7). Energy-harvesting and power-analysis verification workflow, adapted from [12].

LoRaWAN Communication Testing

The communication performance evaluation involves testing multiple LoRaWAN settings to identify the most energy-efficient configuration. The evaluation considers spreading factor, bandwidth, transmission power, time-on-air, received signal strength indicator (RSSI), and signal-to-noise ratio (SNR). A complete field-test campaign is planned to measure packet delivery ratio (PDR), latency, and energy per transmission at different distances and gateway locations. These measurements are essential because communication reliability and energy consumption are strongly affected by radio configuration, antenna placement, terrain, and environmental conditions.

Sensor Calibration & Environmental

The calibration and validation process, shown in Fig. 8, involves calibrating the soil moisture, temperature, and water-level sensors; conducting stress tests under rain, heat, humidity, and partial shading; and verifying measurement accuracy by comparing the outputs against commercial reference sensors. Particular attention is given to soil-moisture calibration because sensor response can vary with soil texture, salinity, and compaction. The calibration stage therefore includes repeated measurements under different soil conditions, followed by software filtering to reduce noise and improve the stability of transmitted readings.

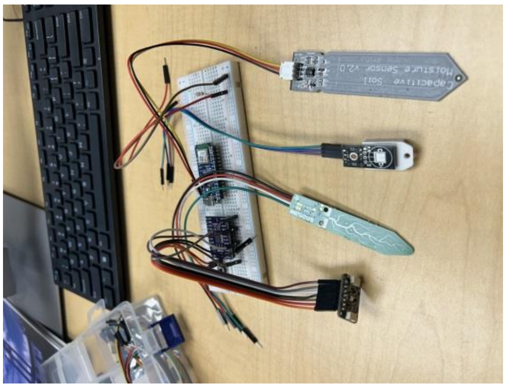

Figure: (8). Sensor Calibration & Environmental

Data Flow

The workflow and the flow of field-acquired data, as illustrated in Fig. 9, are described through a sequence of interconnected steps that outline how information is collected, processed, and transmitted throughout the system. Sensor data are first sampled locally, filtered by the embedded firmware, and checked against predefined thresholds. The node then determines whether the data should be transmitted immediately, stored temporarily, or delayed until the next scheduled reporting interval. This data-management approach reduces radio usage while preserving responsiveness to important agricultural events.

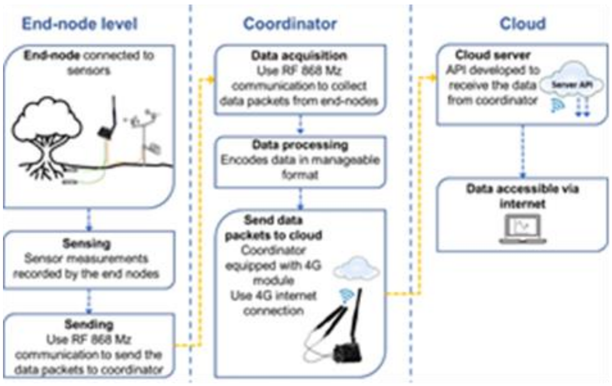

Figure: (9). Wireless sensing system flow description, adapted from [13].

RESULTS

The results summarized in Fig. 10 should be interpreted as a design-level comparison between the baseline configuration and the improved architecture rather than as a complete long-term experimental dataset. The revised design is expected to reduce unnecessary power consumption, improve solar charging stability, strengthen LoRaWAN link reliability, and enhance sensor measurement consistency. However, the complete numerical validation of these improvements requires additional long-duration testing under real agricultural conditions. For this reason, the manuscript emphasizes the technical design improvements and clearly identifies detailed quantitative evaluation as an ongoing extension of the work.

To respond to the reviewer's recommendation for stronger validation, the revised manuscript now clarifies the specific metrics that will be used in the continuing evaluation phase: sleep-mode and active-mode power consumption, battery lifetime under different duty cycles, daily harvested solar energy, packet delivery ratio, latency, RSSI/SNR variation, and energy per transmission. These metrics will support statistical analysis using repeated measurements and comparison with recently published LoRaWAN and energy-harvesting sensor platforms.

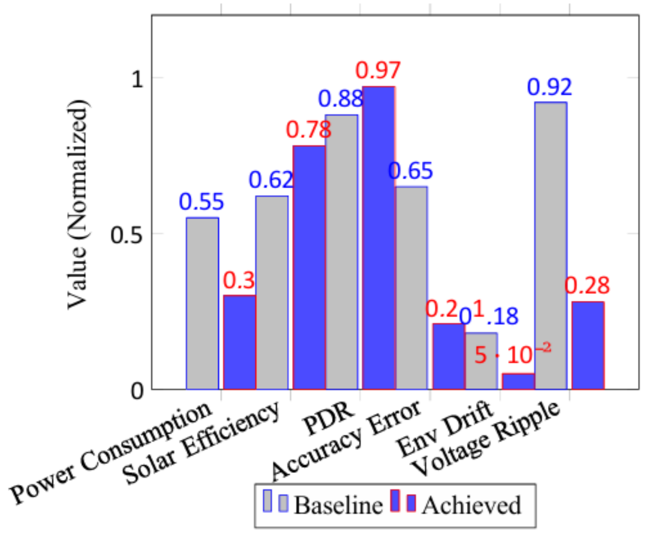

Figure: (10). Comparison of baseline and improved system performance across key metrics.

DISCUSSION

The proposed system is positioned as a technically verified architecture that integrates solar harvesting, MPPT-based charging, LiFePO4 energy storage, adaptive duty cycling, and LoRaWAN Class A communication within a single agricultural monitoring platform. Compared with many conventional smart-farming nodes, the design emphasizes energy autonomy, low maintenance, and modular sensor integration. The qualitative comparison in Table 1 summarizes how the proposed architecture relates to representative LoRaWAN-based agricultural IoT approaches reported in the literature.

Future validation will use repeated measurements under controlled and field conditions. The planned analysis will report mean values, standard deviations, and operating ranges for the main performance metrics. It will also compare the proposed platform with existing agricultural IoT and LoRaWAN systems using common indicators such as energy autonomy, communication reliability, and sensor accuracy. This future work will strengthen the quantitative contribution of the system while preserving the current manuscript as a design-focused and technically grounded development study.

Table (1). Qualitative comparison between the proposed architecture and representative LoRaWAN-based agricultural IoT systems.

Parameter	Proposed system	Representative literature
Solar energy harvesting	Yes; PV-based autonomous supply	Commonly used in outdoor agricultural IoT systems
MPPT-based charging	Integrated to improve harvested-energy utilization	Included in some systems, but not always combined with LoRaWAN
LiFePO4 energy storage	Selected for stability, cycle life, and outdoor suitability	Less frequently emphasized than Li-ion/Li-Po storage
Adaptive duty cycle	Used to reduce unnecessary sensing and transmission events	Reported in some low-power designs
LoRaWAN Class A operation	Used for low-power wide-area communication	Common in agricultural LoRaWAN deployments
Multi-sensor monitoring	Soil moisture, temperature, humidity, pH, and water level	Common, but sensor sets vary by application
Quantitative field validation	Defined through power, battery, PDR, latency, RSSI/SNR, and energy metrics	Reported in mature field studies with long-term campaigns

CONCLUDING

This paper presents the development of a low-power, solar-powered IoT sensor network tailored for precision agriculture. By integrating LiFePO4 storage, MPPT-based energy harvesting, adaptive duty cycling, and LoRaWAN communication, the proposed system addresses the critical challenge of energy autonomy in remote agricultural deployments. The revised manuscript strengthens the technical description of the power-management subsystem, communication protocol, sensor integration, and data-flow process while clarifying the validation metrics required for future quantitative assessment.

The ongoing refinements in PCB design, sensor calibration, and gateway configuration aim to transition the prototype from a proof-of-concept platform to a scalable and field-ready monitoring system. Although comprehensive long-term quantitative measurements remain part of the continuing research plan, the present work establishes a practical architecture for sustainable agricultural sensing and provides a clear framework for future experimental validation. Ultimately, this research contributes to the advancement of sustainable farming practices by reducing maintenance overhead, improving energy efficiency, and supporting data-driven agricultural management.

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