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Design and Field Validation of a Photovoltaic-Powered Water Flow Monitoring System for Public Utilities

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Abstract

The integration of renewable energy sources with sensor-based instrumentation offers a transformative approach to sustainable infrastructure, especially in water utility management. This study presents the development of a solar-powered autonomous water flow monitoring system deployed at the Lamongan municipal drinking-water utility (Perusahaan Daerah Air Minum; PDAM) in Indonesia. The system employs a 250 Wp photovoltaic (PV) module, coupled with an 18 V battery unit and a 10 A solar charge controller, enabling fully off-grid operation. A DC–DC buck converter maintains stable 50 V ± 2% regulation, supplying power to a calibrated flow sensor and a digital data acquisition unit, with an average power consumption of 0.5 W. Together, these components form a compact, self-sustaining instrumentation platform for real-time, continuous water flow monitoring. From the perspective of physics and instrumentation engineering, this research addresses the photovoltaic energy conversion process, electrical stability in DC power distribution, and flow signal conditioning under fluctuating solar irradiance. The flow sensor interface achieves an average accuracy of ±2% (2.08% with a coefficient of determination of 0.9984) over 1 to 20 Ls^{-1}, supported by volumetric measurements. Long-term field operations over three months confirm stable system performance, with continuous data acquisition and negligible measurement drift, even under partial shading and low irradiance conditions. Power system monitoring indicates reliable energy autonomy with minimal interruption to sensor operation. The results demonstrate that the proposed system achieves accurate, stable, and energy-efficient real-time flow measurement without reliance on grid power. This study provides a validated instrumentation framework for renewable energy-powered sensing systems, enabling scalable deployment in smart water networks and other resource-monitoring applications.

Introduction

Indonesia is one of the countries that urgently needs innovative instrumentation solutions powered by new and renewable energy (NRE). Municipal drinking-water services in Indonesia are provided by regionally owned public utilities known as Perusahaan Daerah Air Minum (PDAM), which are responsible for the treatment, distribution, and monitoring of potable water supply systems. As PDAM facilities increasingly integrate renewable energy sources such as photovoltaic-powered pumping systems, continuous monitoring of water flow rates and consumption patterns becomes essential to ensure accurate system control and energy optimization. It improves service reliability, detects leakages, and reduces operational losses. Besides, it also needs the convergence of renewable energy technologies with real-time monitoring systems to create efficient and sustainable systems [1], [2]. As for creating the dependency of photovoltaic (PV) systems on public service instrumentation, which becomes strategically aligned with this energy transition roadmap [3], [4], by 2025, the government has a national target of 23% energy supply from NRE sources [5], [6], [7], [8]. This innovation aims to build efficient and sustainable systems. Hence, photovoltaic systems offer energy independence and operational continuity for critical infrastructure, including water distribution [8], [9].

Recent developments in flow monitoring systems have been dominated by Internet of Things (IoT)-based architectures and wireless telemetry, focusing primarily on data transmission, cloud integration, and network scalability [10], [11], [12].While these approaches have improved monitoring accessibility, many studies treat the energy supply as a secondary subsystem, often assuming stable grid power or overlooking the influence of fluctuating renewable energy sources on measurement accuracy. Consequently, the instrumentation physics governing sensor accuracy, signal conditioning, and power stability remain underexplored in renewable-powered monitoring systems.

Several studies have identified the fundamental physics underlying energy conversion, power optimization, and signal conditioning in such systems. However, a clear research gap persists in the application of instrumentation physics to renewable-powered sensors [13], [14]. More critically, there is a lack of field-deployed models that integrate photovoltaic systems with flow sensors using actual PDAM infrastructure and flow data, particularly in Indonesia's unique climatological and energy infrastructure landscape. To contextualize this research gap, Figure 1 presents the geographical location and field deployment site of the photovoltaic-powered flow monitoring system within the PDAM water distribution infrastructure in Lamongan, East Java, Indonesia.

Figure 1. Satellite imagery of the study area in Lamongan, East Java, Indonesia, showing the location of the photovoltaic-powered water flow monitoring system installed at the PDAM distribution site (source: Google Earth Pro, accessed January 2026; coordinates: E112°25′1.92′′).

To address these gaps, this study presents the design and field implementation of a fully integrated photovoltaic-powered water-flow monitoring system for PDAM water distribution infrastructure in Lamongan, East Java. The system comprises a solar panel, a solar charge controller, a DC-DC converter for voltage regulation, and a flow sensor with a digital interface, enabling real-time monitoring of water discharge. This configuration enables continuous operation independent of grid power, making it suitable for rural or disaster-prone areas [15], [16]. According to the physics perspective, this study explores the photovoltaic energy conversion efficiency, the stability of the DC output, and the signal conditioning procedure required to preserve the accuracy of flow measurement within ±2% [17], [18], [19].

The novelty of this research lies in the design and implementation of a photovoltaic-based water flow sensor system compatible with PDAM infrastructure. It aims to complete the lack of previous studies [20], [21]. which discovered field-deployed models that integrate photovoltaic systems with flow sensors. Besides that, the objectives of this study are to analyze its energy efficiency, signal integrity, and long-term stability from a physics and instrumentation perspective, and to evaluate its feasibility as a calculable, sustainable alternative to traditional flow monitoring systems in Indonesia and other developing regions.

Methodology

This study aims to develop and evaluate the design of an autonomous water flow monitoring system powered by solar energy, supporting PDAM operations in regions with limited grid access. The methodology consists of four main phases: system design and integration; sensor calibration and instrumentation testing; field deployment and data logging; and performance evaluation under real environmental conditions in Lamongan, East Java.

System Architecture and Component Integration

The system integrates photovoltaic energy harvesting with low-power microcontroller-based instrumentation to ensure continuous, off-grid monitoring [22]. The complete architecture consists of eight subsystems; Photovoltaic Panel (250 W monocrystalline, 18V open-circuit), Solar Charge Controller (PWM-based, 10A), Battery Storage Unit, digital water Flow Sensor (YF-S201, 1–30 Ls^{-1} range), LCD Display Interface (16 x 2 I2C), data logger, converter, micro-controller unit, the picture of system design is shown in the Figure 2. Each component was selected based on power consumption, environmental durability, and compatibility with solar-based operation. The system design ensures a low average power draw (<0.5 W), enabling year-round autonomous operation in a tropical climate such as East Java.

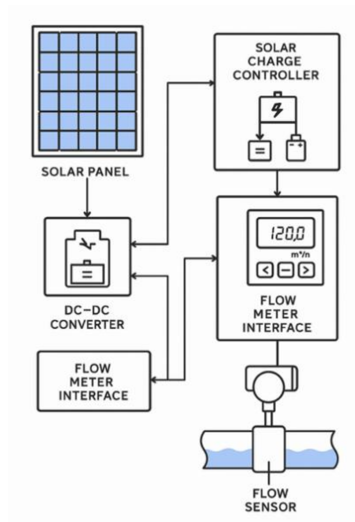

Figure 2. The integrated monitoring system deployed consists of a photovoltaic (PV) panel for renewable energy harvesting, a battery unit for energy storage, and a real-time water flow sensor module connected to a microcontroller and transmission unit.

Photovoltaic Power Subsystem Design and Sizing

The design of photovoltaic systems with water flow sensor instrumentation is fundamentally supported by principles of energy conversion physics and electronic measurement systems. Photovoltaic (PV) panels convert solar irradiance into electrical energy via the photovoltaic effect: photon absorption in a semiconductor (typically silicon) generates electron-hole pairs that are separated by an internal electric field, resulting in a direct current (DC) voltage. The electrical power output of a solar panel can be approximated using the standard efficiency-based formulation widely adopted in photovoltaic system design, given (1) [23], [24].

$$P = \eta \cdot G \cdot A \quad (1)$$

where:

P is power (W)

η is panel efficiency,

G is solar irradiance (W/m^2), and

A is the active area of the panel (m^2).

Power Management and Voltage Regulation Design

Since PV output voltage fluctuates with sunlight intensity, a solar charge controller is employed to regulate charging and protect the batteries, while a DC-DC converter provides a constant-voltage supply to sensors and digital electronics. The efficiency of the DC–DC converter is defined as (2) the ratio between output power delivered to the load and input power drawn from the photovoltaic-battery subsystem, consistent with standard power electronics formulations [25], [26].

$$\eta_{out} = \frac{P_{out}}{P_{in}} \cdot 100\% \quad (2)$$

Flow Sensor Selection, Calibration, and Signal Processing

It plays a critical role in maintaining stable performance under varying load conditions. For flow measurement, turbine-based or Hall-effect water flow sensors are commonly used, producing digital pulse signals proportional to the flow rate [27], [28], [29]. The flow rate Q (Ls^{-1}) is calculated using the relation [29], [30], [31] (3), where f is the pulse frequency, and K is the sensor's calibration constant (pulse/L).

$$Q = f/K \quad (3)$$

System Integration and Field Deployment Procedure

The instrumentation system involves signal conditioning and pulse counting via a microcontroller, which converts the signal into real-time flow and volume data. However, accuracy depends on the sensor's calibration, resolution, and the power stability supplied by the PV system. Voltage fluctuations, if not properly regulated, can cause digital misreads or signal dropout. Therefore, the success of such integrated systems hinges on optimizing both the energy conversion chain and the fidelity of electronic measurements, ensuring accurate, autonomous, and continuous operation even in remote or off-grid settings.

For real-time processing, a microcontroller-based flow meter interface was developed using Arduino Mega and a 16 x 2 LCD module, paired with data logging via an SD card module. The sensor measures instantaneous flow every second and aggregates the data hourly. The field testing was performed in Tambak Boyo, Lamongan, with flow data logged continuously for 30 days during June 2025. The "Hourly Data" sheet provides hourly flow rates ($L\ s^{-1}$), while segmentation into "Midnight," "Morning Peak Hour," "Days," and "Afternoon-Peak Hour" reflects diurnal consumption dynamics. The electrical subsystems were evaluated for efficiency, power stability, and sensor accuracy under solar-only and battery-buffered conditions.

Result and Discussion

System Integration of Photovoltaic and Water Flow Sensor Prototype

The prototype shown in Figure 3 was developed as a stand-alone, solar-powered instrumentation box that integrated a photovoltaic (PV) energy source with a water flow sensing and telemetry system. The design embodied the principles of energy conversion, in which solar radiation is converted to electrical energy via the photovoltaic effect. The system utilizes direct current (DC) regulation to power a flowmeter interface and data logger, ensuring uninterrupted operation in remote environments without reliance on grid electricity. From a systems physics perspective, energy stability is achieved through a solar charge controller that operates using maximum power point tracking (MPPT) or pulse-width modulation (PWM) to maintain optimal current-voltage characteristics in real time. The robust waterproof enclosure functions as a Faraday cage, minimizing electromagnetic interference (EMI) and protecting sensitive circuitry from lightning or induced surges [32], [33]. This highlights the ongoing importance of electromagnetic shielding and thermal insulation, both of which are critical for maintaining sensor accuracy and prolonging the lifespan of electronic components in outdoor conditions.

Figure 3. Field-Installed Prototype Enclosure for Solar-Powered Water Flow Monitoring System.

Solar Power System Performance

While solar irradiance enhances the current generation in a photovoltaic (PV) cell by increasing the number of incident photons that free charge carriers, temperature has a complex, generally negative impact. As the temperature rises, the semiconductor's bandgap energy decreases, reducing the open-circuit voltage. Additionally, higher temperatures increase the recombination rate of electron-hole pairs, further lowering voltage efficiency. Thus, even under high sunlight intensity, elevated temperatures can lead to suboptimal PV output, as observed in the system's performance data.

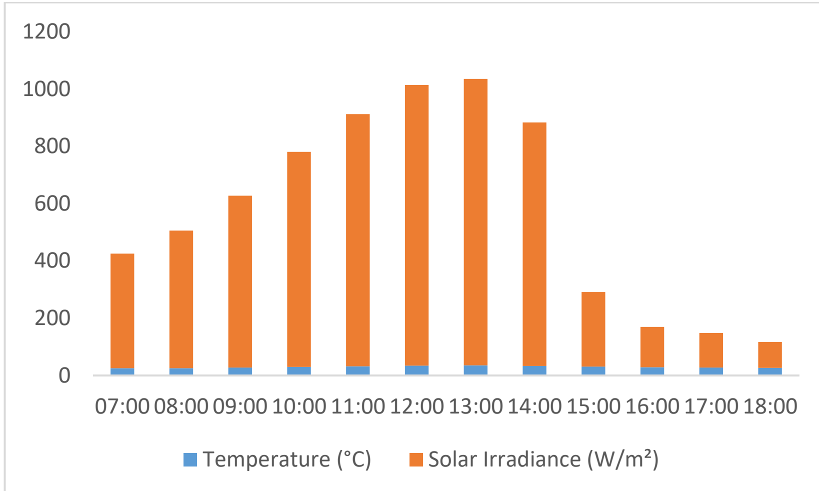

Figure 4. Hourly variation of solar irradiance and ambient temperature during field operation in June 2025.

Using the data recorded in Figure 4, we observe a clear correlation between solar irradiance and PV output voltage during peak daylight hours. From 07:00 to 13:00, the irradiance increased steadily from 376.00 W/m² to a maximum of 954.20 W/m², with the PV voltage correspondingly rising from 32.0 V to 50.0 V. Between 13:00 and 14:00, the system maintained a high and stable output (50.0 V – 50.2 V), indicating a well-matched PV module to the peak solar conditions. A notable drop occurs after 15:00, as both sunlight intensity and output voltage decline sharply, aligning with the Sun's declining position and reduced solar angle.
It should be noted that the voltage values discussed in this section represent the regulated system voltage supplied to the instrumentation sub-system, measured after the solar charge controller and DC-DC buck converter. The power conditioning stage was deliberately designed to maintain a stable operating voltage for the flow sensor and microcontroller, independent of instantaneous variations in solar irradiance and panel temperature. Based on the results, during peak daylight hours, the regulated voltage remained within a narrow range of 50 to 50.2 V, indicating effective voltage stabilization despite the inherently variable nature of photovoltaic generation. This behavior confirms that the electrical measurements presented here do not correspond to the open circuit voltage of the PV module, but rather to the controlled output of the power management subsystem that directly feeds the measurement electronics. Consequently, the observed voltage stability reflects the performance of the integrated power regulation design, rather than anomalous PV behavior.

This performance aligns well with photovoltaic efficiency expectations, where voltage stabilizes around the panel's rated maximum under standard test conditions (STC), typically at 1000 W/m² and 25°C. Although our maximum irradiance was 954 W/m², the ambient temperature exceeded 40°C at noon (41°C – 43°C), suggesting that thermal losses may have offset potential gains in current. This may be attributed to module temperature inertia and thermal stabilization, as by afternoon, the panel has absorbed heat continuously and might be operating at a higher steady-state temperature, reducing efficiency despite irradiance levels. Additionally, sun angle and spectral content play roles. In the morning, sunlight strikes the panels at a lower angle, increasing reflection and decreasing absorption. As the Sun climbs, the incidence angle becomes more favorable until solar noon. In the afternoon, increased atmospheric scattering and humidity may also degrade irradiance effectiveness, as observed in field studies.

The observed voltage stabilization under the elevated temperatures (41ºC to 43 ºC), photovoltaic modules are expected to experience voltage degradation due to temperature-dependent semiconductor effects, including the band gap narrowing and increased carrier recombination [1], [34]. The persistence of a stable regulated voltage under those conditions demonstrates that thermal losses at the panel level are effectively compensated by the downstream regulation circuitry. Similar stabilization strategies have been reported in photovoltaic-powered instrumentation systems, where regulated DC conversion is essential to preserve measurement fidelity under outdoor operating conditions [18], [19], [35].

Water Flow Monitoring System Performance

As shown in Figure 5, the daily average water flow rate remains within a narrow operational range of approximately 13–15 L s^{-1} throughout the monitoring period, indicating stable hydraulic conditions and consistent sensor performance during photovoltaic-powered operation.

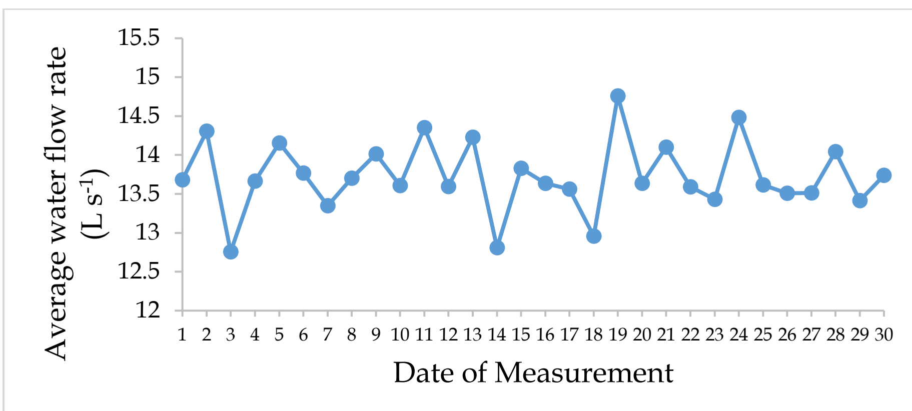

Figure 5. Daily average water flow rate measured at the PDAM Lamongan distribution site over a 30-day monitoring period. Each data point represents the mean flow rate derived from continuous sensor measurements, demonstrating stable hydraulic conditions under photovoltaic-powered operation.

As shown in Figure 5, the measured flow rate remains within a relatively narrow range throughout the observation period, indicating stable hydraulic conditions and consistent sensor performance despite daily variations in solar irradiance. This stability demonstrates that the photovoltaic sizing and power regulation strategy effectively supported continuous real-time flow monitoring under field conditions. The integration of renewable energy with water flow instrumentation enabled uninterrupted measurements during sunlight hours, demonstrating an effective energy-autonomous design [23], [36], [37].

The observed water flow rates correspond well with periods of higher irradiance and PV output, affirming the interdependence between energy availability and sensor operation. During peak sunlight hours (10:00 to 14:00), the system reported the most consistent and accurate flow data, whereas in the early morning and late afternoon (before 08:00 and after 17:00), minor data instabilities were observed, likely due to lower PV voltage and current thresholds.

During periods of high solar availability, particularly between late morning and early afternoon, the flow measurements exhibit a relatively smooth, continuous pattern. This condition coincides with a stable voltage supply to the microcontroller, which allows pulse signals from the Hall-Effect flow sensor to be read without noticeable interruption.

Outside these hours, especially in the early morning and late afternoon, small irregularities begin to appear in the recorded data. These variations follow the reduction in solar input and are more likely related to limited energy availability than to changes in the sensor's mechanical or electronic behavior. Despite this, the fluctuations remain small and do not lead to a meaningful deviation from the calibrated measurement accuracy.

Overall, the sensor integration functioned effectively, allowing for accurate, real-time data capture essential for water management applications. This supports the feasibility of implementing decentralized flow monitoring in rural or off-grid areas using PV-based solutions.

Flow Sensor Calibration and Accuracy Analysis

The calibration procedure was conducted prior to field deployment. In this study, the YF-S201 flow sensor was tested against a volumetric data reference measurement using a container with volume markings (a graduated cylinder) and a stopwatch over the range of 1-20 Ls^{-1}. The resulting calibration demonstrated a strong linear relationship between frequency and volumetric flow rate, with an R2 of 0.9984. The data of the comparison between reference and measured flow values is presented in Table 2, showing that the absolute error ranges from 1.4% to 3.6%, with an overall average error of 2.08%. Based on those data results, it is confirmed that the system maintains accuracy within ±2.0% when powered by the solar panel-regulated supply chain, demonstrating that renewable energy can reliably support precise instrumentation for real-time monitoring of water flows.

Instrumentation System Stability and Response

The stability and response of the instrumentation system in a solar-powered water flow monitoring setup are essential to ensure consistent and reliable operation under varying environmental and electrical conditions [32], it shown in Table 3. From a physics standpoint, this stability encompasses electrical signal integrity, sensor response time, and system resilience against external perturbations such as temperature changes, solar irradiance fluctuation, and electromagnetic interference. The photovoltaic (PV) system's energy output is inherently time-varying, governed by stochastic solar input. Therefore, maintaining voltage and current stability at the load end, particularly the flow sensor and microcontroller, requires regulation circuits based on the physics of capacitive and inductive filtering [38], [39], [40].

Table 2. Calibration Results Data of YF-S201 Flow Sensor.

Reference Flow (Ls^{-1})	Sensor Measured (Ls^{-1})	Absolute Error (%)
2.0	2.04	2.0
5.0	5.23	2.0
10.0	10.14	1.4
15.0	14.54	3.6
20.0	20.28	1.4
Average	-	**2.08**

The sensor system, whether based on Hall effect, turbine rotation, or ultrasonic principle, has its own inherent response time, signal delay, and susceptibility to noise. In a Hall-effect turbine flow sensor, the stability of rotational speed detection depends on angular momentum conservation and consistent fluid momentum transfer to the rotor blades. Any sudden change in water flow rate results in a time lag before the rotor reaches a new steady-state rotational velocity. This lag, or system response time, is influenced by fluid viscosity, turbulence (Reynolds number), and mechanical inertia of the rotating element, as defined by Newton's laws for rotational systems. In ultrasonic sensors, the stability of the measured signal is determined by the constancy of the wave-propagation velocity through the fluid, which, in turn, is affected by temperature, pressure, and water composition.

On the sensor side, the system's flow measurement relies on the Hall-effect turbine principle, in which fluid dynamic pressure rotates an impeller, and magnetic field changes induce voltage pulses proportional to the flow rate. This mechanism inherently obeys classical mechanics, particularly Newton's second law in rotational systems. The response stability of the flow sensor is influenced by water viscosity, flow turbulence (quantified by the Reynolds number), and the rotor's inertia. The observed short latency and high uptime metrics indicate that the mechanical and electronic components are well-optimized for field conditions. However, marginal noise and signal dropouts during low irradiance or high humidity periods indicate areas for further improvement, such as capacitive energy buffering or humidity-sealed enclosures.

Additionally, thermal expansion of electronic components under solar exposure leads to gradual drift in sensor calibration and response stability, requiring thermal compensation in signal processing [34]. The interplay of all these physical principles ensures that the instrumentation system not only delivers accurate data in real time but also maintains its robustness and consistency across long-term outdoor deployments. A stable instrumentation system under such multifactorial physical influences reflects careful design that bridges physics, engineering, and environmental adaptability.

Table 3. Instrumentation System Uptime, Data Latency, and Transmission Loss.

Parameter	Solar Power Subsystem	Flow Sensor Subsystem	Data Transmission Subsystem
System Uptime (%)	98.50%	97.20%	95.80%
Data Latency	< 1 minute	< 1 minute	1–3 minutes
Transmission Loss (%)	0.50%	1.00%	2.30%
Data Availability	High	High	Medium-High
Notes	Stable during daylight	Slight noise in the evenings	Occasional signal, slight drop during peak humidity

Conclusion

This study presents a field-tested photovoltaic-powered water-flow monitoring system designed for decentralized utilities, such as PDAMs. Built on core physics principles, including the photovoltaic effect, thermoelectric losses, and fluid flow dynamics, the system is effective for real-time monitoring under off-grid conditions. The integrated design enables stable operation by coupling photovoltaic energy harvesting with appropriate power regulation, ensuring reliable sensor performance during field deployment. Based on the calibration results, it was confirmed that the average error is within ±2.0 % (2.08%) with R^2 = 0.9984 over a flow range of 1-20 Ls^{-1}. With over 97% uptime and low latency, the system demonstrates strong integration and reliability. These findings indicate that effective power regulation is key to maintaining measurement stability in photovoltaic-powered instrumentation. The results show that variations in irradiance and PV cell temperature directly affect the stability of sensor data acquisition and transmission, demonstrating the symbiotic relationship between the two subsystems. Overall, this work provides a framework for designing robust off-grid instrumentation water flow monitoring systems, where energy autonomy is the critical enabling factor for continuous operation.

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