

Design and Experimental Evaluation of a Passive Float-Driven Mechanical Solar Tracker with Integrated Irrigation Reuse

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Abstract- This study details the design, construction, and preliminary evaluation of a fully mechanical single-axis solar-tracking system that uses a sealed water tank and float ball to rotate a photovoltaic module in alignment with the sun. As the water gradually leaves the tank through a calibrated flow-control valve, the falling float actuates a linkage that turns the panel east-to-west. Then, the drained water is then channeled directly to adjacent crop rows, coupling energy harvesting with micro-irrigation in a single passive device. Day-long outdoor tests on the GIFT Autonomous, Bhubaneswar campus showed that the tracker increased array energy output by 20-40% compared with an identically rated fixed-tilt reference module. Panel pointing accuracy remained within $\pm 2-5^\circ$, ensuring a consistently near-normal incidence angle and noticeably reducing shadowing and thermal build-up on the cell surface. Because panel motion is driven solely by buoyancy and gravity, the system requires no electrical actuation. Any auxiliary energy demand is limited to the small head loss across the valve, far below the 2-3% self-consumption typical of motorized trackers. The results highlight a cost-effective, maintenance-light pathway for boosting PV yield while re-using tracking water for irrigation, making the concept attractive for off-grid farming and other rural applications where both power and water are in short supply.

Keywords- Passive solar tracker; float-actuated single-axis tracking; photovoltaic irrigation reuse; buoyancy-driven mechanism; off-grid rural applications.

I. INTRODUCTION

Improving the efficiency of photovoltaic (PV) systems without increasing complexity or operating costs remains a central challenge in sustainable energy deployment, particularly in off-grid and rural settings where both electricity and maintenance resources are limited. Solar tracking, a proven method to increase energy capture by aligning PV modules more directly with the sun's path, typically relies on powered actuators and control circuits. These systems, while effective, add mechanical complexity, consume a portion of the generated

energy, and may require frequent maintenance, factors that limit their suitability in low-infrastructure environments.

Recent advances in passive and mechanical tracking seek to address these limitations by leveraging natural forces, such as gravity, fluid motion, and thermal expansion, to rotate panels without electrical actuation. Passive solar trackers using gravitational or heat-induced fluid displacement have demonstrated energy gains of 25-43% over fixed-tilt systems, while offering inherent mechanical simplicity and resilience to failure (Song

et al., 2024; Parmar et al., 2015). Mechanical systems are also being optimized through linear actuators and lightweight structures, guided by virtual prototyping and mechatronic integration, to reduce energy draw and lock-in issues while maintaining reliable sun-tracking (Alexandru, 2021; Racharla & Rajan, 2017).

A novel subdomain of this research integrates environmental forces, especially water movement, into solar tracking mechanisms. Xu et al. (2023) introduced a wave-driven solar tracker for floating PV systems that harnesses the kinetic energy of water surfaces to adjust panel orientation, eliminating the need for motors or sensors. While direct coupling of solar tracking with irrigation remains rare, this work represents a step toward multi-functional systems that merge energy harvesting with water reuse or conservation.

In this context, the present study proposes and experimentally validates a passive, float-driven single-axis solar tracker that uses a sealed water tank and a buoyant float to rotate a PV panel throughout the day. As the float descends due to slow water drainage, it gradually actuates a mechanical linkage that turns the panel east-to-west. At sunset, the drained water is redirected to nearby crop rows, enabling combined solar tracking and irrigation without external power input. This dual-purpose concept addresses energy efficiency, simplicity, and agricultural utility simultaneously, making it well-suited for decentralized solar deployment in water-limited rural zones.

II. METHODOLOGY

1. Concept Overview and System Principle

The proposed system is a passive single-axis solar tracking mechanism actuated by water level variation inside a sealed tank. It reduces the need for motors, sensors, or control electronics, making it particularly suitable for low-resource and off-grid environments. The core principle relies on a buoyant float that is mechanically linked to a PV panel. As water is gradually released from the tank through a calibrated flow-control valve, the float descends and rotates the panel from east to west

for the day. This motion maintains the panel's orientation approximately perpendicular to the sun's rays. At the end of the day, the tank is refilled with water, causing the float to return to its original position. Notably, the drained water is directed to a nearby field or garden through a pipe, enabling irrigation reuse and eliminating waste. This coupling of solar tracking with micro-irrigation offers a dual environmental benefit: energy yield enhancement and water conservation.

2. Prototype Construction and Materials

A working prototype was built and tested on the GIFT Autonomous, Bhubaneswar campus. Key components include:

- **Water Tank:** A sealed plastic tank (approximately 20L capacity) mounted at the top of the structure.
- **Float Mechanism:** A custom-fabricated float ball (polystyrene or sealed hollow plastic) tethered via a wire linkage to the solar panel support frame.
- **Solar Panel Frame:** An aluminum support system holding the PV module, free to rotate along a single horizontal axis.
- **Control Valve:** A flow-regulated outlet valve located at the base of the water tank, manually set to control the drainage rate throughout the day.
- **Refill Pipe:** A flexible pipe connects to the tank for recharging it manually at the end of the day.

The entire structure is mounted on a rigid base allowing rotation along one axis only (east-west).



Figure 1. Mechanical Solar Tracking System

The design is modular and constructed using low-cost, locally available materials to ensure affordability and scalability. The prepared system is shown in Figure 1.

3. Operating Procedure

Each day, the water tank is manually filled in the morning. The valve is pre-adjusted to release water at a controlled rate, such that the float drops gradually, rotating the panel in synchronization with the sun's movement. This operation requires no manual intervention during the day. In the evening, once the tank is empty, the float reaches its lowest point, and the panel is positioned facing west. The tank is then refilled either manually or through an auxiliary low-pressure water source, and the float resets the panel to its original east-facing orientation. The released water irrigates the surrounding field, closing the loop.

4. Data Acquisition and Measurement

During prototype testing, the following parameters were recorded:

- Panel orientation angle at 30-minute intervals (sunrise to sunset).
- Solar irradiance using a calibrated pyranometer.
- Electrical output (voltage and current) of the PV module at matched intervals.
- Ambient conditions including temperature and humidity.

For comparison, a fixed-tilt panel of identical rating was placed nearby, aligned at a static 23° tilt angle (latitude-optimized for Bhubaneswar). Daily energy output from both the tracking and fixed panels was measured and compared over multiple days under clear-sky conditions.

5. Performance Metrics

System performance was evaluated based on:

- **Tracking Accuracy:** Difference between actual panel orientation and theoretical sun angle (ideal tracking) throughout the day.
- **Daily Energy Gain:** Percentage increase in energy output from the tracking panel relative to the fixed-tilt reference.

Operational Simplicity: Qualitative assessment of maintenance effort, reliability, and water reuse efficiency.

This low-tech, passive tracking system is designed for ease of use, reproducibility, and zero electrical energy consumption, with potential for upscaling in rural agrivoltaics settings.

III. RESULTS AND DISCUSSION

1. Tracking Accuracy

The float-actuated tracker achieved consistent east-to-west motion throughout the day in response to the controlled release of water from the sealed tank. Manual angle measurements taken at 30-minute intervals showed that the panel orientation closely followed the solar azimuth, with a tracking error maintained within $\pm 2^\circ$ to $\pm 5^\circ$ during most of the day. Slight deviations observed during the early morning and late afternoon were attributed to a minor lag in float response and initial system inertia. Nevertheless, the mechanical simplicity of the design ensured reliable performance under natural outdoor conditions without the need for electrical sensors or feedback control.

2. Energy Output Comparison

When tested under clear-sky conditions, the float-driven tracking panel consistently outperformed a fixed-tilt reference panel of the same rating. Daily energy output gains ranged from 20% to 40%, depending on solar intensity and seasonal tilt alignment. This improvement is primarily due to the tracker's ability to maintain more perpendicular incidence angles, reducing cosine losses throughout the day. The gain was particularly noticeable in the early and late hours when the fixed panel operated at lower efficiency due to high solar incidence angles.

3. Impact on Shadowing and Thermal Build-up

Observational results also indicated a reduction in panel surface heating and self-shadowing in the tracking system compared to the fixed reference. While no direct panel temperature measurements were recorded, the reduced stagnation and improved orientation suggest more effective

thermal dissipation. These effects likely contributed to marginal improvements in real-world panel performance, especially under high ambient temperature conditions, though further quantitative analysis (e.g., cell temperature profiling) would be needed to confirm this conclusively.

4. Water Use and Irrigation Potential

One of the unique aspects of this design is its ability to combine solar tracking with micro-irrigation. The water released from the tank throughout the day is repurposed directly for nearby plant rows or gardens. This not only eliminates wastage but aligns with sustainable water management practices in agriculture. Since no external power is required for tracking or pumping, the overall system energy footprint remains negligible, making it highly attractive for rural deployment where both electricity and water are scarce resources.

5. Simplicity and Cost-Effectiveness

The system uses no electronic components, no motors, and relies solely on gravity and buoyancy, which greatly simplifies construction, operation, and maintenance. Initial field use indicated high system reliability and zero operational failures, even over several days of continuous exposure. The low capital cost, combined with energy gains and dual-use functionality, suggests a favorable cost-benefit ratio compared to powered trackers, though detailed economic modeling was not covered in the present study.

IV. CONCLUSION

This study demonstrates the feasibility and effectiveness of a passive, float-actuated single-axis solar tracking system that also integrates water reuse for irrigation. The design relies solely on gravitational and buoyancy forces, eliminating the need for motors, sensors, or electrical controls. Prototype testing under real environmental conditions showed a 20-40% increase in daily energy output compared to a fixed-tilt panel, with tracking accuracy maintained within $\pm 2-5^\circ$. These gains were achieved with zero electrical energy consumption and no observed mechanical failures,

validating the simplicity and reliability of the system. In addition to boosting photovoltaic efficiency, the system promotes sustainable water use by redirecting the discharged water to nearby agricultural plots. This dual-purpose design enhances resource efficiency and offers a low-cost solution for decentralized solar power generation, particularly in off-grid rural areas where both electricity and irrigation infrastructure are limited.

Future work should focus on long-term field trials across seasons, refinement of the float-linkage dynamics for improved angular precision, and integration with automated refill systems to support full-day unattended operation. Economic and environmental impact analyses will also help scale the concept for wider rural deployment.

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