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From Mechanical Rotation to Optofluidic Precision: Evaluating Liquid-Prism Beam-Steering as a Sustainable Alternative for Concentrating Photovoltaic Systems

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ABSTRACT

Improving renewable energy technologies is essential for meeting global sustainability objectives, such as United Nations Sustainable Development Goal 7 (SDG 7). While photovoltaic energy generation is expanding rapidly — currently accounting for approximately 6.5% of global electricity generation and over 35% of installed renewable capacity — maximizing real-world operational module yield remains an ongoing engineering optimization challenge. Conventional dual-axis electromechanical trackers increase annual energy yield by up to 30-40% over fixed-tilt panels depending on regional latitude and climatic conditions, but introduce high capital expenditures, frequent mechanical failures, and significant parasitic energy consumption. Optofluidic beam-steering via electrowetting-on-dielectric (EWOD) liquid prisms has emerged as a novel, non-mechanical alternative designed to dynamically refract sunlight without heavy structural movement. However, this technology is strictly tailored for CPV that rely on Direct Normal Irradiance (DNI), rather than conventional flat-plate solar panels. This systematic review synthesizes the physical principles, energy efficiency, structural footprint, and long-term durability of EWOD-driven liquid prisms compared to conventional dual-axis and single-axis trackers. While EWOD liquid prisms eliminate mechanical motors and gear backlash, their real-world applicability is physically constrained by a narrow angular steering window (typically $10^{\circ} to\ 15.3^{\circ}$), optical reflection/absorption losses (12-22%), high driving voltages ($50V - 150V$), and unproven outdoor durability (TRL 3–4). Consequently, as established by our regional comparative synthesis, optofluidic beam-steering is not a direct replacement for panel-level trackers, but offers a viable supplementary or micro-tracking solution when paired with static wide-acceptance concentrators or coarse primary tracking.

Keywords: Concentrating Photovoltaics (CPV), Electrowetting-on-Dielectric (EWOD), Optofluidic Beam-Steering, Solar Tracking, Liquid Prism, Direct Normal Irradiance (DNI).

INTRODUCTION

SDG 7 aims to ensure access to affordable, reliable, sustainable, and modern energy for all (United Nations, 2015). Achieving this objective requires continuous enhancements in renewable energy conversion efficiency and system-level reliability. While global renewable capacity expands rapidly—spearheaded by major markets including China, the United States, and India (IRENA, 2025; World Population Review, 2026) — optimizing module-level energy capture remains critical. Target 7.4 of SDG 7 specifically emphasizes international cooperation on clean energy research and technology (United Nations, 2015). As solar power assumes an increasingly dominant role in global electricity infrastructure, optimizing tracking precision while minimizing Operation and Maintenance (O&M) failure points is imperative (Cheng et al., 2013).

While mechanical solar trackers remain the current industry standard, their reliance on complex physical movement introduces significant structural challenges, including high maintenance demands, vulnerability to wind stress, large safety clearance zones known as "swept volume" that limit land-use efficiency, and efficiency loss. Because SDG 7 emphasizes reliability and affordability, systems affected by frequent mechanical failures present a critical challenge for sustainable energy deployment.

Liquid-prism beam-steering technology has therefore been investigated as a potential alternative to conventional mechanical tracking, particularly for CPV architectures (Cheng et al., 2013; Apostoleris et al., 2016). Optical concentrators rely strictly on DNI — direct, parallel sunbeams focused onto small, ultra-high-efficiency multi-junction cells. Unlike standard flat-plate photovoltaic modules, which capture both direct beam light and scattered diffuse sky radiation from all directions, CPV systems require continuous, high-precision alignment to maintain optical focus. Refractive liquid prisms steer parallel sunlight by dynamically altering liquid interface angles via electrowetting, but cannot focus scattered diffuse radiation. Consequently, optofluidic tracking is not a drop-in replacement for standard flat-plate PV, but rather a targeted alternative for CPV systems where mechanical dual-axis tracking is traditionally required. Furthermore, because refractive liquid interfaces are physically constrained to narrow angular ranges, optofluidic technology does not serve as a standalone replacement for full 180° diurnal tracking, but rather as a fine-steering mechanism within hybrid tracking architectures or wide-acceptance CPV modules.

Although existing review literature addresses isolated aspects of solar tracking and liquid optics, a critical research gap remains at their intersection. Comprehensive reviews by Apostoleris et al. (2016) evaluate tracking-integrated optical concentrators and mechanical tracking mechanisms, but do not analyze non-mechanical optofluidic architectures or their physical interfacial limits. Conversely, reviews dedicated to tunable liquid prisms (e.g., Zhang et al., 2025) focus broadly on device physics and fabrication across diverse domains — such as biomedical imaging, adaptive displays, and microfluidic devices — without evaluating solar beam-steering, quantifying optical transmission losses against parasitic electrical savings, or assessing solar land-use constraints. Consequently, no prior review provides an unified engineering evaluation comparing EWOD liquid prisms directly against mechanical single- and

dual-axis trackers across angular kinematics, parasitic versus optical energy trade-offs, spatial ground coverage, and field maintenance failure modes. To address this gap, this review presents a parameter-by-parameter comparative synthesis between electromechanical trackers and EWOD optofluidic beam-steering, establishing the physical boundaries, net energetic performance, and real-world deployment feasibility of solid-state tracking in CPV systems.

METHODOLOGY

This research was conducted as a systematic literature review to evaluate non-mechanical optofluidic beam-steering against conventional electromechanical tracking architectures in CPV systems. To ensure transparency, reproducibility, and rigorous documentation of the data extraction workflow, the research design adheres to the structural principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework.

Search Strategy and Databases

Electronic databases, specifically ScienceDirect (Elsevier) and Google Scholar, were systematically queried to identify primary research published between 2020 and 2026. To ground the analysis in established physical and architectural fundamentals, this primary search was supplemented by seminal pre-2020 literature (e.g., Kang, 2002; Cheng et al., 2013; Apostoleris et al., 2016; Clement & Park, 2016) covering core EWOD equations and initial optofluidic CPV tracking concepts.

The exact Boolean search string applied across both platforms was:

(("liquid prism" OR "optofluidic beam steering" OR "electrowetting-on-dielectric" OR "EWOD") AND ("solar tracking" OR "concentrating photovoltaics" OR "CPV" OR "optical tracking") AND ("efficiency" OR "angular range" OR "parasitic power" OR "maintenance" OR "reliability"))

Inclusion Criteria	**Exclusion Criteria**
Research evaluating EWOD, liquid prisms, or tunable liquid interfaces applied specifically to CPV or solar beam-steering.	EWOD or liquid-optics studies designed strictly for display technology, lab-on-a-chip microfluidics, or biomedical imaging.
Studies reporting empirical or theoretical performance data on either conventional	Standard flat-plate photovoltaic systems operating without optical concentration or dynamic tracking optics.

electromechanical solar trackers or optofluidic beam-steering systems.	
Studies providing explicit numerical data on at least one key performance metric.	Patent filings lacking experimental validation data, editorials, opinion pieces, non-peer-reviewed web publications, or market overviews lacking physical/optical modeling.

Table 1. Inclusion and exclusion criteria utilized for article screening during the systematic literature review.

Retrieved documents meeting the baseline inclusion criteria underwent formal critical appraisal to ensure data integrity. Studies were evaluated based on a three-tier quality assessment matrix:

1. **Methodological Validity:** Experimental designs were required to report clear liquid-pair compositions (e.g., oil-water interfaces), specific dielectric thicknesses (d), and exact input voltage parameters.
2. **Dataset Reliability:** Quantitative data regarding steering angles or transmission percentages were cross-verified against verified physical formulas (such as Snell's Law and the Lippmann-Young framework) to flag anomalous modeling configurations.
3. **Peer-Review Verification:** Priority status was given to papers indexed in reputable engineering databases (e.g., IEEE Xplore, Elsevier ScienceDirect, Optica Publishing Group, and MDPI) with clear conflict-of-interest disclosures.

PRISMA Diagram

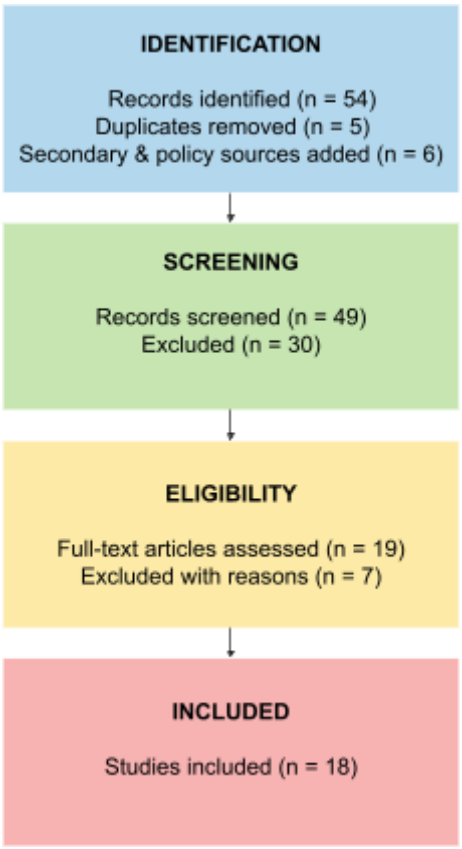


Figure 1: PRISMA flow diagram documenting the systematic literature selection, exclusion pipeline, and final review extraction strategy for comparing electromechanical trackers against optofluidic beam-steering systems.

As mapped out in the PRISMA flow diagram (Figure 1), the initial literature search strategy yielded a total of 54 primary records. Following the removal of duplicates ($n = 5$) and the strategic integration of critical secondary policy and institutional datasets ($n = 6$), a baseline cohort of 49 unique records moved forward into the primary screening phase.

During the initial title and abstract screening stage, 30 records were systematically excluded due to lack of operational alignment with solar parameters, focus on non-solar macrofluidic pumps, or application to distinct lens geometries. This left a remainder of 19 full-text articles to be exhaustively assessed for eligibility against the predefined PECO framework.

Upon full-text evaluation, 7 articles were excluded with specified reasons, including missing primary engineering fields, duplicate research data loops, or heavy reliance on unverified commercial blog entries. This filtering cycle yielded a finalized, high-fidelity cohort of 18 studies completely included within this systematic synthesis, establishing full data consistency between our graphical reporting workflow and the final reference bibliography index of this paper.

STRUCTURAL DESIGN

In utility-scale solar deployment, single-axis tracking (SAT) represents the predominant industry standard, offering a mature reliability record and capturing roughly 20% to 30% more annual energy than fixed-tilt systems at a favorable levelized cost of electricity. However, CPV architectures strictly require continuous, high-precision two-axis alignment ($< 0.5^{\circ}$ optical tracking error) to keep DNI focused onto high-efficiency micro-cells, necessitating dual-axis tracking (DAT) configurations. While dual-axis tracking can boost annual energy yield by 30% to 40% relative to fixed-tilt installations, these performance metrics are highly conditional; empirical solar datasets establish that tracking yield gains depend heavily on regional geographic latitude, seasonal orbital sun paths, and the localized atmospheric clearness index - failing to yield substantial energetic advantages in climates dominated by scattered diffuse overcast radiation (Apostoleris et al., 2016; Poulek & Kozelka, 2026).

Achieving full two-axis mobility requires substantial mechanical infrastructure driven by macroscopic hardware, including DC electric motors, planetary gearboxes, slewing drives, linear actuators, and electronic tracking sensors (Jamroen et al., 2020; Hammas et al., 2025).



Figure 2. Anatomy of a dual-axis mechanical solar tracking system highlighting structural components including azimuth and tilt linear actuators, pivot joints, and mounting hardware (Hammas et al., 2025).

While effective for heavy array support, this mechanical dependency subjects chain transmissions, slewing bearings, and pivot joints to continuous physical movement, wind load torque, and gear fatigue. Operational failure analyses indicate that motorized actuators, gearboxes, and position sensors account for a substantial portion of unscheduled tracking maintenance and system downtime compared to static arrays (Jamroen et al., 2020; Rotar et al., 2021). Furthermore, traditional dual-axis trackers require heavy structural foundations and high structural clearance, increasing installation complexity and capital expense—particularly on load-constrained commercial rooftops (Cheng et al., 2013).

Conversely, optofluidic solar tracking eliminates macroscopic structural movement entirely by executing light manipulation at the material level. Rather than tilting the entire physical panel payload via motors, optofluidic platforms maintain a completely stationary, low-profile outer profile. Alignment with the shifting solar vector is achieved internally by sealing fluid channels directly over the photovoltaic receivers, substituting mechanical wear profiles with solid-state electrical routing. This structural simplification bypasses traditional electromechanical stress points, shifting the engineering focus from drivetrain kinematics to localized fluidic boundary controls.

PHYSICAL PRINCIPLES OF OPTOFLUIDIC BEAM STEERING

Optofluidic beam-steering utilizes EWOD to achieve non-mechanical fluid steering without external gears, motors, or gantry structures. Importantly, EWOD does not alter the intrinsic refractive indices of the liquids. Instead, an applied electric potential modifies the solid-liquid interfacial energy, altering the contact angle and physically reorienting the interface between two immiscible liquids of differing refractive indices.

The electromechanical response of the fluid interface to an applied voltage V is governed by the Young-Lippmann equation:

$$\cos\theta(V) = \cos\theta_0 + \frac{\varepsilon_0 \varepsilon_r V^2}{2\gamma d} \qquad \text{(Eq. 1)}$$

where:

- $\theta(V)$ is the voltage-dependent contact angle,
- θ_0 is the initial equilibrium contact angle at zero applied voltage ($V = 0V$),

- ε_0 is the vacuum permittivity ($8.854 \times 10^{-12} F/m$),
- ε_r is the relative dielectric constant (permittivity) of the insulating dielectric layer,
- d is the thickness of the dielectric layer,
- γ is the oil–water liquid–liquid interfacial tension, representing the interfacial energy between the two immiscible fluids rather than a standard liquid–vapor surface tension.

To operate as a beam-steering prism rather than a focusing lens, the liquid boundary must stay flat and tilted, rather than curved. If equal voltage is applied to all surrounding electrodes, the liquid curves symmetrically, changing its focal length (like a liquid lens). However, if different voltages are applied to opposite sides, it tilts the flat surface at an angle relative to the base, creating a dynamic liquid prism.

When DNI passes through this tilted planar interface, the ray refracts according to Snell's Law:

$$n_1 \sin\alpha = n_2 \sin\beta \quad \text{(Eq. 2)}$$

where:

- n_1 is the refractive index of the first liquid medium (typically an aqueous phase, $n_1 \approx 1.33$),
- n_2 is the refractive index of the second liquid medium (typically a dielectric oil, $n_2 \approx 1.40 - 1.50$),
- α is the angle of incidence relative to the normal of the tilted liquid interface,
- β is the angle of refraction relative to the interface normal.

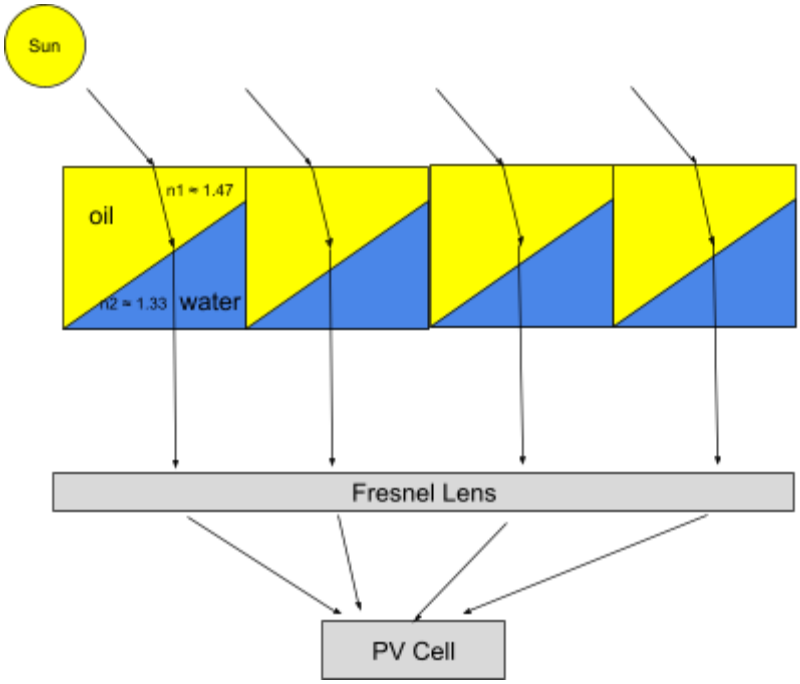


Figure 3: Schematic cross-section of an integrated optofluidic CPV tracking panel. Parallel incident solar rays pass through the upper oil layer ($n_1 \approx 1.47$) and undergo sharp refraction at the voltage-controlled, dynamically tilted oil-water interface ($n_2 \approx 1.33$). The liquid prism array straightens off-axis sunlight into a uniform vertical output, enabling a fixed secondary optical condenser (Fresnel lens) to concentrate the Direct Normal Irradiance (DNI) onto a small, stationary high-efficiency PV receiver.

By dynamically adjusting the interface tilt angle via differential EWOD voltages, the angle of incidence at the fluid boundary changes continuously, producing a smooth, variable angular deflection in the transmitted beam.

The maximum optical steering range achievable by an EWOD liquid prism is fundamentally constrained by two physical mechanisms:

1. **Narrow Refractive Index Contrast (Δn):** Because liquid prisms rely on immiscible liquid-liquid pairs (e.g., water and silicone oil), the refractive mismatch is relatively small ($\Delta n = n_2 - n_1 \approx 0.07 - 0.17$), limiting the maximum deflection angle per interface transition compared to solid glass prisms in air.
2. **Contact Angle Saturation:** Although the Young-Lippmann equation predicts continuous contact angle reduction with increasing voltage, physical EWOD systems experience contact angle saturation at high electric field strengths, preventing further interface tilting regardless of voltage increases.

As a result of these physics-based constraints, empirical liquid-prism architectures achieve maximum optical beam deflection ranges that vary across individual studies. Specifically, Cheng et al. (2013) achieved a tracking range of ±10.3° along a single axis, while Clement and Park (2016) reported a maximum deflection angle of ±11.8°. Most recently, advanced structural and multi-electrode cell configurations synthesized by Zhang et al. (2025) reached an ultimate steering limit of 15.3°.

Because a standard tracking cycle requires spanning up to 180° of diurnal solar motion across the celestial vault, these tight operational windows prove that optofluidic steering cannot replace conventional mechanical dual-axis tracking entirely. Instead, liquid-prism arrays are physically restricted to functioning as supplementary micro-tracking layers within hybrid tracking frameworks or as active fine-steering inputs paired directly with static, wide-acceptance optical concentrators.

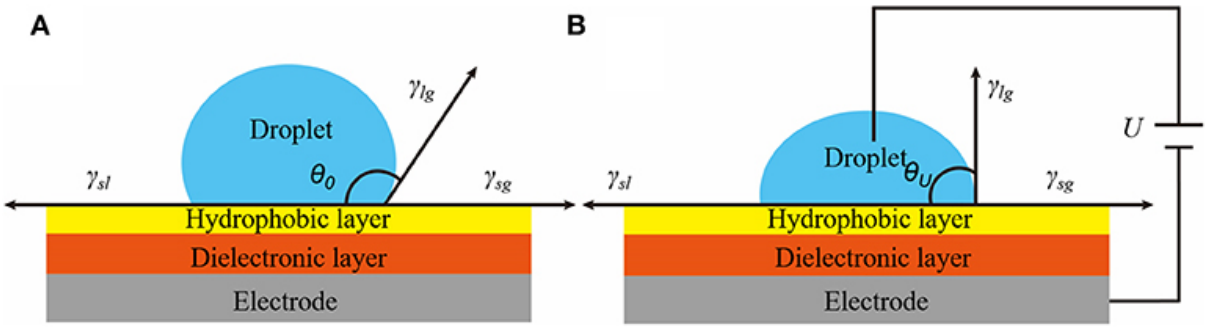


Figure 4. Cross-sectional schematic of droplet electrowetting showing (A) the initial contact angle (θ_0) without voltage and (B) the modified contact angle (θ_U) when voltage U is applied across the dielectric and hydrophobic layers (adapted from Yi et al., 2020).

ENERGY CONSUMPTION

A key consideration in evaluating tracking mechanisms is their net energetic efficiency, which balances electrical parasitic draw against optical efficiency losses. Traditional dual-axis mechanical trackers do not draw power continuously. Instead, drive motors move in discrete, intermittent steps (typically 5 to 15 seconds of operation every few minutes) to follow the solar path. Published energy yield analyses demonstrate that mechanical tracking drive consumption represents a small fraction of total generated power, typically accounting for only 0.2% to 1.5% of annual electrical yield (approximately 1.0 to 3.0 Wh/m²/day) (Jamroen et al., 2020; Hammas et al., 2025).

In contrast, EWOD optofluidic actuation eliminates mechanical motor draw but introduces electrical capacitive power requirements. Systems operate at AC or DC drive voltages ranging from 20 V to 80 V (Cheng et al., 2013). Under static DC holding conditions, current draw is governed strictly by dielectric

leakage ($J_{leak} \approx$ 10 nA/cm² to 1 μA/cm²), yielding nanowatt-level static power dissipation ($P_{static} \leq 0.05 W/m^2$). However, because the sun moves continuously across the sky ($\sim 15^{\circ}/hour$) and periodic AC frequency modulation ($100Hz\ to\ 1kHz$) is required to prevent dielectric charge trapping, EWOD prisms require ongoing dynamic updates. The dynamic power consumption density for EWOD array actuation is governed by:

$$P_{dynamic} = \frac{1}{2} CV^2 f + J_{leak} V \quad \text{(Eq. 3)}$$

drawing approximately 10 to 100 μW/cm² ($0.1 to\ 1.0 W/m^2$) during continuous diurnal tracking—a low but non-zero dynamic load.

Furthermore, a complete energy analysis must account for the optical losses caused by the fluid layers, which reduce sunlight before it reaches the solar cell:

1. **Fresnel Reflection Losses:** Incident solar rays cross five distinct refractive index boundaries (Air / Top Glass / Water / Oil / Substrate Glass / Air), incurring an 8% to 11% reflection penalty across uncoated interfaces.
2. **Volumetric Absorption:** Water and organic dielectric oils exhibit wavelength-dependent absorption bands, particularly in the near-infrared (NIR) spectrum ($> 900nm$), resulting in an additional 3% to 5% optical loss.
3. **Chromatic Dispersion:** Because liquid refractive indices vary with wavelength ($\Delta n(\lambda)$), broadband sunlight undergoes spectral dispersion ($\sim 0.5^{\circ} to\ 1.2^{\circ}$), causing focal spot broadening and reducing the optical intercept factor in CPV systems by 2% to 4%.

Consequently, while mechanical trackers lose 0.2% to 1.5% of their generated power to motors, optofluidic systems lose a massive 12% to 22% of their light due to reflection and absorption ($\tau_{opt} \approx$ 75% to 88%). This loss of light is the main energetic drawback of solid-state liquid beam-steering.

SPATIAL REQUIREMENTS

A key distinction between mechanical trackers and optofluidic panels lies in their structural footprint and spatial layout requirements. Dual-axis mechanical trackers rotate massive panel arrays across broad elevation and azimuth arcs, requiring a substantial "swept volume"—a wide clearance zone around each tracker to prevent structural collisions (Apostoleris et al., 2016). This physical rotation profile limits deployment flexibility, particularly on commercial rooftops or uneven terrain.

Conversely, optofluidic panels maintain a flat, stationary outer envelope, eliminating physical swept-volume hazards and enabling low-profile integration on wind-exposed structures and rooftops (Cheng et al., 2013). However, claims regarding land-use efficiency require nuance: at utility scale, stationary optofluidic panels cannot be placed arbitrarily close together. Ground installations remain governed by inter-row shading constraints (Ground Coverage Ratio / GCR), where row-to-row pitch spacing is necessary to prevent adjacent panels from casting shadows on one another at low solar elevation angles. Thus, while optofluidics eliminates mechanical collision clearance zones, row spacing for optical shading remains an inescapable constraint for ground-mounted arrays.

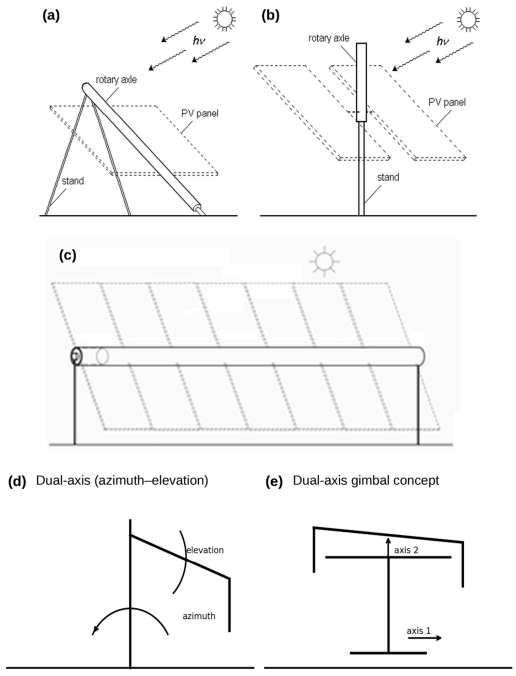


Figure 5. Overview of common mechanical single-axis (a–c) and dual-axis (d, e) solar tracking mechanical architectures. The geometric rotation paths map out the dynamic orientation arcs that dictate system footprint clearance and ground-use spacing (Poulek & Kozelka, 2026).

MAINTENANCE CONSIDERATIONS

Outdoor durability relies on resisting environmental stress and mechanical wear. Traditional dual-axis trackers present large exposed surfaces prone to aerodynamic drag, torsional stress, dust accumulation, and friction degradation (Apostoleris et al., 2016). To model these vulnerabilities mathematically, closed-loop tracking circuits utilize fault coverage-aware metrics and hardware-in-the-loop self-testing frameworks to map error propagation profiles across microcontroller blocks (Rotar et al., 2021).

Long-term fleet availability data from commercial tracking facilities demonstrate that motorized assemblies introduce continuous operational maintenance overhead—primarily driven by drive-gear wear, motor actuator burnout, and tracking sensor calibration drift—contrasting with the structurally passive profiles characteristic of static mounting configurations (Poulek & Kozelka, 2026).

In contrast, sealed optofluidic panels maintain a flat, low-profile stationary design that minimizes environmental wind load profiles and eliminates common electromechanical failure modes like gear stripping, shaft misalignment, or motor driver failure (Cheng et al., 2013). However, optofluidic frameworks substitute these traditional mechatronic risks with distinct physicochemical reliability challenges regarding long-term microfluidic containment, hermetic edge seal degradation, fluid evaporation loops, and UV-induced chemical yellowing of the outer dielectric layer. Because existing optofluidic solar collection architectures remain confined to short-duration laboratory proof-of-concept testing environments (TRL 3–4), extended outdoor field deployment data across diverse climatic zones are mandatory before long-term solid-state durability projections can be validated.

COMPARISON TABLE

Performance Parameter	**Single-Axis Trackers (SAT)**	**Dual-Axis Trackers (DAT)**	**Optofluidic (EWOD) Systems**	**Comparative Trade-off & Feasibility Assessment**
Technology Readiness Level (TRL)	**TRL 9** (Commercial utility standard)	**TRL 9** (Commercial standard for high CPV)	**TRL 3–4** (Laboratory proof-of-concept)	**Commercial Maturity:** SAT/DAT are fully bankable; EWOD is confined to early-stage experimental validation.

Target PV Module Scope	Flat-plate silicon, thin-film, and low-concentration PV	CPV ($\leq 0.5^{\circ}$ alignment) & high-DNI flat-plate	Integrated micro-Concentrating Photovoltaic (μ -CPV) arrays	**Scope:** Mechanical trackers accommodate standard flat-plate panels; EWOD requires micro-concentrator cell integration.
Angular Steering Range	Single-axis diurnal arc ($\pm 45^{\circ} to \pm 60^{\circ}$)	Full hemispherical coverage ($0^{\circ} to 360^{\circ}$ azimuth, $0^{\circ} to 90^{\circ}$ elevation)	Narrow steering cone ($\pm 10^{\circ} to \pm 15.3^{\circ}$)	**Kinematics:** EWOD cannot track wide diurnal arcs without secondary optical steps or steep panel pre-tilting.
Optical Transmission Efficiency	~ 98%-100% (Standard front glass cover)	~ 98%-100% (Direct beam path)	78%-88% (12%-22% reflection & liquid absorption loss)	Optical Overhead: EWOD suffers an inherent 12% to 22% loss of light passing through its liquid layers and glass interfaces.
Diffuse Light Harnessing	**High** (Absorbs global horizontal & diffuse radiation)	**High** on flat-plate PV; **Zero** on high-concentration CPV	**Negligible / Zero** (Micro-lenses reject diffuse light)	**Radiation Capture:** EWOD and CPV harvest Direct Normal Irradiance (DNI) only, underperforming in overcast climates.

Operating Voltage & Actuation	$12V\ to\ 24V\ DC$ or $120V\ to\ 240V\ AC$ electromechanical motors	24V to 48 V DC or 120 to 480 V AC dual-drive motors	30 to 120 V_{rms}AC (1-10 kHz) EWOD actuation	Actuation: EWOD uses higher voltage but negligible current (μA range), yielding low instantaneous active power.
Energy Yield Gain vs. Fixed	+20% to +30% annual yield gain	+30% to +40% annual yield gain	Variable beam-alignment yield (offset by optical losses)	**Yield:** Gains depend heavily on latitude and direct-to-diffuse radiation ratio (clearness index).
Parasitic Power Draw	0.1% - 0.5% of annual system generation	0.5% - 1.5% (1.0-3.0 $Wh/m^2/day$)	< 0.01% active draw (< 1.0 mW/m^2 holding power)	**Parasitic Losses:** EWOD eliminates motor power draw, but this advantage is outweighed by its optical transmission losses.
Estimated Capital Cost Premium	+\$0.08-\$0.15/W_p over fixed-tilt	+\$0.30-\$0.50/ W_p over fixed-tilt	High prototype CapEx; unpriced mass-manufacturing scale	**Cost:** SAT offers the lowest Levelized Cost of Electricity (LCOE); EWOD cost viability remains unproven at scale.

Spatial Footprint & Layout	Linear row spacing dictated by Ground Coverage Ratio ($GCR \approx 0.35 - 0.5$)	Swept-volume clearance required; lower packing ($GCR \approx 0.2 - 0$)	Flat profile (zero swept volume); ground layout still constrained by GCR	**Land Use:** EWOD enables low-profile rooftop mounting, but utility ground arrays still require GCR spacing to prevent inter-row shading.
Primary Maintenance & Failure Modes	Drive gear wear, motor actuator failure, sensor drift	High O&M overhead: gear stripping, motor burnout, joint wear	Zero mechanical wear; seal failure, droplet evaporation, UV yellowing	**Reliability Trade-off:** Mechanical wear (SAT/DAT) versus fluid containment and chemical degradation risks (EWOD).

Table 2. Quantitative synthesis across single-axis trackers, dual-axis trackers, and EWOD optofluidic beam-steering architectures (synthesized from Cheng et al., 2013; Apostoleris et al., 2016; Jamroen et al., 2020; Rotar et al., 2021; Zhang et al., 2025).

DISCUSSION

The comparative synthesis conducted in this review demonstrates that optofluidic beam-steering offers a possible alternative to traditional mechanical trackers by eliminating gear wear, motor parasitic draw, and physical rotation. However, rather than serving as an immediate universal replacement for mechanical tracking, EWOD liquid prisms introduce distinct physical, energetic, and manufacturing trade-offs that constrain their deployment to specific Photovoltaic (PV) architectures (Cheng et al., 2013).

To place optofluidic beam-steering within the broader context of current solar optics scholarship, EWOD liquid prisms should be evaluated alongside alternative reduced-mechanical and non-mechanical tracking methodologies. As detailed by Apostoleris et al. (2016), alternative frameworks include localized microtracking systems and wide acceptance-angle optical concentrators. Microtracking architectures minimize the spatial structural footprint by shifting small, internal lens arrays over stationary solar cells rather than tilting the entire heavy panel assembly, keeping the outer module frame completely flat. Alternatively, wide-acceptance concentrators utilize specialized static optical geometries, such as non-imaging compound parabolic concentrators (CPCs), to collect off-axis direct solar beams across a broader spatial window without requiring real-time tracking corrections. Integrating EWOD liquid prisms as an active macrofluidic steering layer directly over these static wide-acceptance concentrators represents

a promising hybrid horizon, enabling high solar concentration factors while maintaining a completely stationary panel envelope.

The primary technical boundary of optofluidic beam-steering is its restricted angular deflection range relative to the sun's diurnal trajectory. While the sun traverses an arc of 180° daily and 23.5° seasonally, reported EWOD liquid prisms achieve maximum beam deflection capped at $10^{\circ} - 15.3^{\circ}$ due to narrow liquid-liquid refractive index contrasts ($\Delta n \approx 0.07 - 0.17$) and contact angle saturation at high voltages (Cheng et al., 2013; Clement & Park, 2016; Zhang et al., 2025). Furthermore, optofluidic tracking introduces a fundamental trade-off between parasitic electrical savings and optical throughput: while EWOD eliminates heavy mechanical motor consumption ($1.0\ to\ 3.0\ Wh/m^2$/day), the multi-interface liquid cell stack imposes an intrinsic 12% to 22% optical transmission penalty resulting from Fresnel reflection, near-infrared fluid absorption, and chromatic dispersion. Consequently, solid-state liquid prisms cannot completely replace mechanical rotation in wide-arc utility-scale installations. Instead, optofluidic beam-steering is most viable within a hybrid tracking framework—where a low-cost, single-axis mechanical tracker handles broad diurnal tracking while the EWOD prism executes rapid, high-precision micro-steering—or in combination with wide-acceptance optical concentrators.

Long-term environmental durability represents another critical barrier to commercial adoption. Because electrowetting systems rely on precisely controlled liquid interfaces enclosed within microfluidic chambers, maintaining stable optical performance under continuous outdoor exposure to ultraviolet (UV) radiation, thermal cycling (-20℃ to 85℃), humidity, and wind-induced vibrations remains unproven in field conditions (Cheng et al., 2013). Minor seal degradation, fluid evaporation, or droplet contamination alters the interfacial surface tension and contact angle response, degrading tracking accuracy and optical alignment.

Manufacturing scalability further complicates commercial transition. Unlike mechanical trackers that leverage mature steel fabrication and standardized drive motors, optofluidic beam-steering requires precision microfabrication, transparent conductive electrode coatings, hydrophobic dielectric thin films, and hermetic fluid encapsulation (Clement & Park, 2016). These requirements increase initial capital expenditure (CapEx) until automated roll-to-roll microfluidic manufacturing processes achieve economies of scale. Finally, because the existing literature is overwhelmingly confined to laboratory proof-of-concept prototypes (TRL 3–4), extended outdoor field trials under diverse climatic conditions are essential to validate long-term reliability and LCOE projections.

ENVIRONMENTAL SUSTAINABILITY AND LIFE-CYCLE DISCUSSION

Evaluating the commercial viability of EWOD optofluidic tracking requires assessing the environmental life-cycle, eco-toxicity, and end-of-life handling of its component materials. Optofluidic cells rely on

immiscible liquid-liquid pairs—typically an aqueous electrolyte and an insulating fluorinated or silicone oil (Cheng et al., 2013; Zhang et al., 2025). While silicone oils exhibit low environmental toxicity, fluorinated dielectric fluids pose potential persistent organic pollutant (POP) contamination risks if released into local soil or groundwater. Furthermore, the hydrophobic dielectric insulating layer incorporates fluoropolymers, while transparent conductive electrodes rely on Indium Tin Oxide (ITO) deposited on glass substrates (Clement & Park, 2016). Indium extraction involves energy-intensive mining with significant environmental footprints and supply-chain vulnerabilities. Unlike standard solar panels and steel frames that fit into existing recycling streams, old EWOD modules are much harder to process at end-of-life. They require special chemical extraction to drain and neutralize fluorinated oils and treat Indium-coated glass before disposal or remelting.

LIMITATIONS

This review has several limitations that should be considered when interpreting its findings. First, because the review is based exclusively on published literature rather than original experimental testing, its conclusions depend on the quality, scope, and consistency of the available research. Second, although the review incorporates recent peer-reviewed studies alongside foundational research, the current body of literature on liquid-prism beam-steering remains relatively limited compared with the extensive research available on conventional mechanical tracking systems. As a result, some conclusions regarding long-term durability, commercial scalability, and maintenance requirements are based on emerging evidence rather than extensive real-world validation.

Furthermore, the reviewed studies employ different experimental methodologies, performance metrics, and testing conditions, making direct quantitative comparisons between liquid-prism and mechanical tracking systems inherently challenging. Finally, because many optofluidic beam-steering technologies remain at the laboratory or prototype stage, long-term outdoor performance data under diverse environmental conditions are still scarce. Future research involving standardized testing protocols and extended field deployments will be essential to validate the long-term practicality and commercial feasibility of these systems.

CONCLUSION

While electromechanical single- and dual-axis trackers remain the commercial standard for utility-scale photovoltaic tracking, their reliance on complex, moving parts creates significant operational and sustainability challenges. Optofluidic liquid-prism beam-steering provides an innovative non-mechanical tracking alternative for CPV systems, utilizing electrowetting-on-dielectric to steer Direct Normal Irradiance without physical module rotation. Although narrow steering angles (15.3°), optical losses (12% to 22%), and unproven outdoor sealing prevent them from being used alone in large flat-plate solar farms, optofluidic systems offer a promising solid-state way to provide fine-steering in hybrid CPV, micro-concentrators, and building-integrated photovoltaics (BIPV). Moving this technology from lab

prototypes to commercial use will require long-term outdoor testing, UV-stable dielectric materials, and better sealing techniques.

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