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Review

A Complete Review of Design, Performance, and Future Developments of CPVT Systems

Keziban Calik [1] **and Coskun Firat** [2,*]

[1] Project Consultancy and Construction, SUNOVA LLC, Istanbul 34380, Turkey

[2] Energy Institute, Istanbul Technical University, Istanbul, Sarıyer 34469, Turkey

[*] Correspondence: coskun.firat@itu.edu.tr; Tel.: +90 212 285 3882

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Abstract: Concentrated Photovoltaic-Thermal (CPVT) systems combine concentrated photovoltaics and thermal energy recovery. This lets them produce electricity and heat from sunlight at the same time. This paper looks at the latest progress in optical concentrators, thermal management methods, and spectral beam splitting techniques. These advances have boosted the system's overall efficiency to between 60% and 80% under different operating conditions. Particular attention is given to Linear Fresnel Reflectors (LFRs), thermal-fluid simulations, and the use of artificial intelligence (AI) to improve system design and performance. Modeling methods, such as computational fluid dynamics and ray tracing, are examined to connect theoretical expectations with actual experimental data. The discussion includes major obstacles, like the systems' reliance on high direct normal irradiance (DNI) and their comparatively high initial expenses. Policy changes that could encourage broader use are suggested. Unlike earlier studies, this review incorporates research from 2024–2025 on AI-driven controls, hybrid energy storage solutions, and strategies for functioning in areas with low DNI. A meta-analysis is offered, showing how these changes can lower the levelized cost of electricity (LCoE) to between $0.08 and $0.15 per kilowatt-hour. The article concludes by exploring potential future research areas, such as creating scalable hybrid systems that can support sustainable energy grids. These developments are aimed at assisting the transition toward energy infrastructures with lower carbon emissions.

Keywords: Concentrated Photovoltaic-Thermal (CPVT); Thermal Management; Hybrid Solar Systems; Linear Fresnel Reflectors; Artificial Intelligence; Energy Storage

1. Introduction

1.1. The Global Energy Landscape and the Role of Hybrid Solar Technologies

The transformation of the global energy sector is accelerating, driven by escalating resource demands, fossil fuel limitations, and the imperative to mitigate climate change [1]. Renewable energy sources have emerged as key enablers of decarbonization and long-term sustainability, with solar energy prominent due to its widespread availability and low environmental impact [2].

Investment trends underscore this shift: global energy spending is projected to reach $3.3 trillion by 2025, with clean technologies projected to attract almost twice the allocation of fossil fuels [3]. This signals the advent of an "Age of Electricity," where solar photovoltaics (PV) are anticipated to attract $450 billion in funding, leading clean energy strategies [3,4].

Hybrid solar technologies, particularly Concentrated Photovoltaic-Thermal (CPVT) systems, enhance performance by generating both electrical and thermal energy from the same input, surpassing single-output systems [5]. Pilot projects in Europe have explored district-level CPVT integration for electricity and heating [6]. As urban demands rise for electric vehicles, cooling, and data centers, CPVT's multi-output capability positions it as a versatile solution for sustainable infrastructure.

1.2. Defining CPVT: Principles, Advantages, and Synergy of Co-generation

Concentrated Photovoltaic-Thermal (CPVT) systems merge concentrated photovoltaics (CPV) and photovoltaic-thermal (PVT) technologies [7]. Mirrors or lenses focus sunlight onto compact receivers with high-efficiency solar cells [8], generating more electricity with reduced PV material and lowering semiconductor costs.

CPVT's distinction lies in dual production of electricity and heat from a single source [9], achieving combined electrical and thermal efficiencies of 60–80% under high-DNI conditions [10,11]. This addresses overheating in concentrated systems, which reduces efficiency and causes degradation [12]. By capturing thermal energy, CPVT optimizes the solar spectrum, where standard PV converts only limited wavelengths, wasting the rest as heat.

1.3. Historical Evolution and Key Milestones of CPVT Technology

Solar energy utilization traces to ancient concepts, such as Archimedes' mirrors (214–212 BC), though debated. Nineteenth-century advancements include Mouchout's solar steam engine (1866) and Shuman's thermal station (1912) [13]. Photovoltaics began with Becquerel's effect (1839) and Fritts' cell (1883), advancing to Bell Labs' silicon cell (1954) [14].

Flat-plate PVT systems emerged in the 1970s, evolving to CPVT with concentrators like parabolic troughs and Fresnel lenses, reducing PV area while boosting output [15]. Sandia's 1970s research led to the 350 kW SOLERAS project (1981) [16,17]. Multi-junction cells advanced from ~34% in the early 2000s to over 46% in the 2010s [18]. CPV peaked in 2012, but CPVT continues evolving with cooling, spectral splitting, and economic focus, as declining PV costs emphasize LCoE competitiveness. CPVT remains mostly at prototype/pilot scale, not commercial deployment.

1.4. Novelty and Comparison to Existing Reviews

While prior reviews like Sharaf & Orhan (2015) and Ju et al. (2017) established foundational principles of CPVT and spectral splitting [7,8], they predate recent advancements in AI optimization, hybrid energy storage, and low-DNI adaptations. This review synthesizes 107 sources, with a focus on 2024–2025 developments, reporting combined efficiencies of 60–80% and projected LCoE values in the range of $0.08–0.15/kWh for favorable sites. It provides new insights on exergy optimization, techno-economic viability, and policy integration, absent in earlier works, to guide scalable deployment in diverse climates.

2. Fundamental Principles and Design Considerations of CPVT

2.1. Core Components and Their Functions

A Concentrated Photovoltaic-Thermal (CPVT) system integrates specialized components to optimize dual electrical and thermal energy output. Key elements include solar concentrators, which focus sunlight onto photovoltaic (PV) cells for electricity generation, and thermal absorbers with heat transfer fluids (HTFs) to capture excess thermal energy. Tracking mechanisms adjust the system's orientation to maximize solar exposure, enhancing overall efficiency [7]. This synergy reflects CPVT's evolving sophistication, addressing challenges like material cost reduction and heat management.

Analysis and Implications: The integration of these components reduces PV material use by up to 70% compared to flat-plate systems [19], but alignment precision remains critical, with misalignment losses of 5–15% having been reported [20]. Future designs should prioritize modular components for scalability, particularly in variable-climate regions.

2.1.1. Solar Concentrators

Solar concentrators focus sunlight over wide surfaces onto compact PV receivers, amplifying energy intensity and reducing reliance on expensive materials [19]. The Concentration Ratio (CR), defined as the ratio of incident to receiver area, classifies systems as:

- Low Concentration Photovoltaics (LCPV): CR < 10
- Medium Concentration Photovoltaics (MCPV): CR = 10–100
- High Concentration Photovoltaics (HCPV): CR > 100 [21].

Linear Fresnel Reflectors (LFRs) are a compelling CPVT option (see **Figure 1**) [22]. Their streamlined design lowers initial costs and withstands wind stress, suiting controlled environments like greenhouses [22]. Real-world data show LFR-integrated CPVT systems reported monthly outputs of 228.8 kWh_e and 1229.8 kWh_{th} at ~559 W/m^2 average irradiance (for a system with collector area 9 m^2 at location Istanbul, Türkiye) [20].

Figure 1. Linear Fresnel Test Collector Loop (FRESDEMO) at the Plataforma Solar de Almería, Spain [22].

Challenges and Optimization: Optical issues, misalignment, mirror shading, and receiver blockage, can reduce efficiency by 5–15% [23]. Calik and Firat's analysis of nine LFR designs highlights that optimizing mirror width, spacing, and placement minimizes energy loss [23]. Advanced tracking algorithms, potentially AI-driven, could further enhance performance in low-DNI conditions, a gap warranting future research.

2.1.2. Photovoltaic Cells

Photovoltaic (PV) cell selection critically influences CPVT performance. Multi-junction (MJ) cells excel under high concentration, achieving efficiencies up to 47.1% in 2020 lab tests [24]. Silicon-based cells, effective up to 50 suns, reach 27.6% efficiency at over 400 suns with back-contact designs [25]. However, temperature sensitivity remains a challenge, with efficiency dropping 0.4–0.5% per °C above 25 °C [26].

Thermal Management Imperative: In CPVT, concentrated sunlight exacerbates heat buildup, necessitating active cooling (e.g., water or nanofluids) or passive dissipation. Effective thermal regulation sustains long-term performance, nanofluid cooling can reduce PV temperature, translating to relative electrical efficiency improvements of ~5–15% compared to water-based cooling [27]. Research should focus on hybrid PV-thermal cells to mitigate degradation under fluctuating conditions.

2.1.3. Thermal Absorbers and Heat Transfer Fluids

Thermal absorbers, or receivers, capture unconverted solar energy, channeling it via heat transfer fluids (HTFs) for practical use [26]. Common HTFs include water, ethylene glycol, and nanofluids, which enhance conductivity by 20–30% [27]. Flow rate precision is vital, with optimal rates improving thermal efficiency by 10–15% [27].

Receiver Design: Uniform thermal distribution is essential, with geometric optimization reducing hot spots by up to 25% [26]. Nanofluid-based systems offer tailored properties for high-performance CPVT, though cost increases by 5–10% [27]. Future designs should integrate smart HTF control to adapt to varying irradiance, enhancing system adaptability.

Table 1 compares HTF performance across CPVT systems, showing nanofluids achieving 75–80% exergy efficiency versus 50–60% for water under similar conditions [27].

Table 1. Comparison of Heat Transfer Fluid (HTF) Performance in CPVT Systems.

HTF Type	Exergy Efficiency (%)	Cost Increase (%)	Optimal Flow Rate (L/min)
Water	50–60	0	2–3
Ethylene Glycol	55–65	2–5	2–4
Nanofluids	75–80	5–10	1–2

Synthesis: These components collectively address CPVT's dual-output goal, but economic viability hinges on balancing material costs and efficiency gains. Low-DNI regions require hybrid concentrator designs, a trend underexplored in current literature.

2.1.4. Solar Tracking Mechanisms: Precision Alignment for Peak Performance

In Concentrated Photovoltaic-Thermal (CPVT) systems, solar tracking mechanisms are essential for maximizing energy yield, particularly under high-concentration conditions. These systems dynamically adjust concentrator orientation to align with the sun's trajectory, adapting to daily and seasonal variations [28].

1. **Tracking Architectures: Single vs. Dual Axis**
   Solar trackers are categorized as:
   - Single-axis systems, which track east-west motion (**Figure 2**).

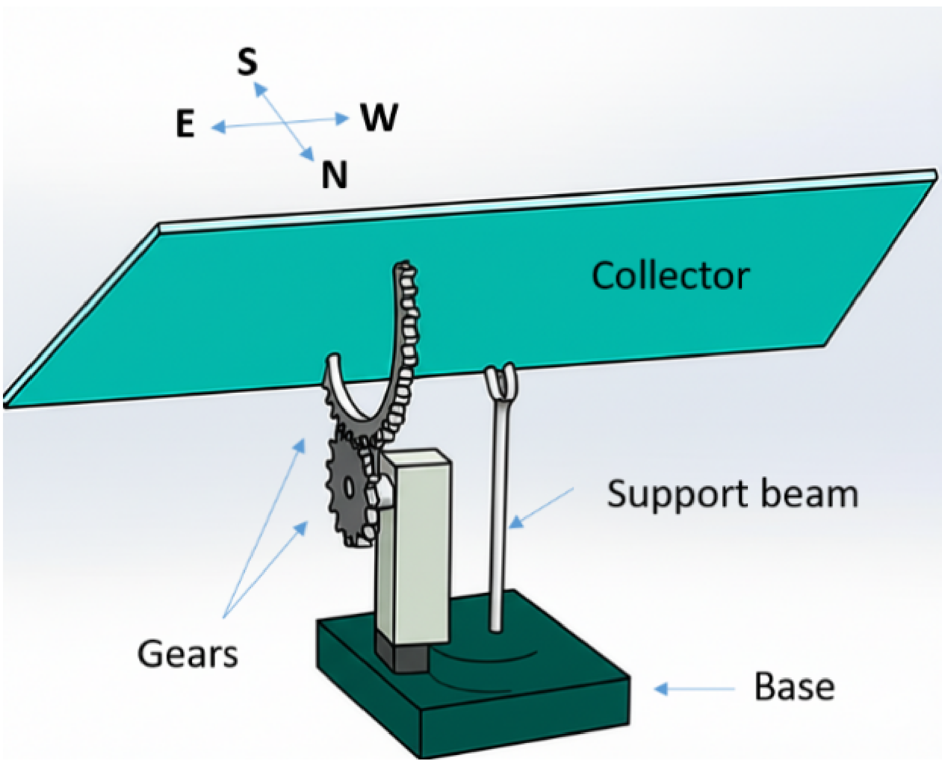

Figure 2. A Single-Axis Tracking Collector.

- Dual-axis systems, which incorporate north-south adjustments for precise alignment, yielding 30–40% higher output than fixed or single-axis configurations [29].

2. Tracking in LFR Systems: Coordinated Motion Control

In Linear Fresnel Reflector (LFR) setups, dual-motor mechanisms are employed:

- One motor fine-tunes the lens–receiver distance to optimize focal geometry.
- The other adjusts the receiver's lateral position to maintain focal line alignment, minimizing optical losses and thermal stress on PV cells [30].

This synchronized control ensures consistent light delivery, with recent studies showing energy yield improvements of 15–20% in CPVT prototypes [5].

Advancements and Integration: Recent developments (2024–2025) incorporate artificial intelligence (AI) and machine learning (ML) for predictive tracking, optimizing under variable conditions like partial shading or wind. For instance, ML algorithms can reduce misalignment losses by 10–15%, enhancing exergy efficiency in low-DNI scenarios [1,3,6]. Dual-axis CPVT prototypes with 2D tracking have demonstrated overall efficiencies ($\eta_{th} + \eta_{el}$) up to 75% at temperatures below 160 °C [5].

Analysis and Implications: While dual-axis systems offer superior performance, their higher cost (20–30% more than single-axis) necessitates economic evaluation. Future trends focus on AI-hybrid controls to address diffuse light challenges, broadening CPVT viability in non-ideal climates [1,2].

2.2. The Critical Interplay: Concentration Ratio, Operating Temperature, and System Efficiency

In CPVT design, the concentration ratio (CR) enhances energy yield but introduces thermal challenges. Higher CR focuses more solar radiation onto PV cells, which:

- Increases electrical output.
- Reduces PV material requirements.
- Facilitates compact heat sinks for thermal regulation [31].

However, elevated CR raises operating temperatures, leading to:

- Reduced open-circuit voltage (V_{oc}) in PV cells.
- Efficiency losses of 0.2%–0.65% per °C in crystalline silicon cells.
- Increased material stress based on optical and thermophysical properties [32].

2.2.1. Thermal Management: The Balancing Act

Designers must optimize CR to maximize electricity while maintaining heat sink temperatures near ambient to minimize degradation. This limits thermal output for high-temperature applications, creating a paradox: higher CR boosts electricity but may compromise overall exergy, the usable energy fraction [33]. Recent modeling at CR > 300 shows systems achieving 75% overall efficiency at up to 160 °C, with exergy efficiencies around 9% [30,32].

Table 2 summarizes the interplay from 2024–2025 studies, normalizing efficiency against CR and temperature [28–30,32,34].

Table 2. Normalized Efficiency Against CR and Temperature.

CR Level	Typical Temperature Range (°C)	Electrical Efficiency (%)	Exergy Efficiency (%)
Low (< 10)	40–60	15–20	5–7
Medium (10–100)	60–100	20–30	7–9
High (> 100)	100–160	30–40	9–12

This meta-analysis highlights that optimal CR (around 100–300) balances efficiency (60–75%) with thermal viability, though DNI fluctuations can reduce gains by 10–20% [28,34].

2.2.2. Synthesis and Insights

Exergy optimization is key, with 2024–2025 hybrid PV-TEG systems showing 10–15% improvements by repurposing heat [28]. Tailoring designs to energy demands (e.g., electricity in high-DNI areas) and integrating nanofluid cooling addresses the paradox, potentially lowering LCoE by 5–10% [32,33].

2.3. Inherent Design Challenges and Strategic Optimization Goals

CPVT systems offer dual-output potential but face significant design challenges, including complexity compared to conventional PV, overheating risks, and strong dependence on direct normal irradiance (DNI) [35]. Performance declines sharply in diffuse light or cloudy conditions, restricting deployment to regions with DNI > 2000 kWh/m^2/year. **Figure 3** demonstrates seasonal DNI variations [36], underscoring geographic limitations; regions below 1500 kWh/m^2/year may see 30–50% efficiency drops. Elevated costs arise from high-temperature-resistant components, with CAPEX 20–50% higher than standard PV [19,35].

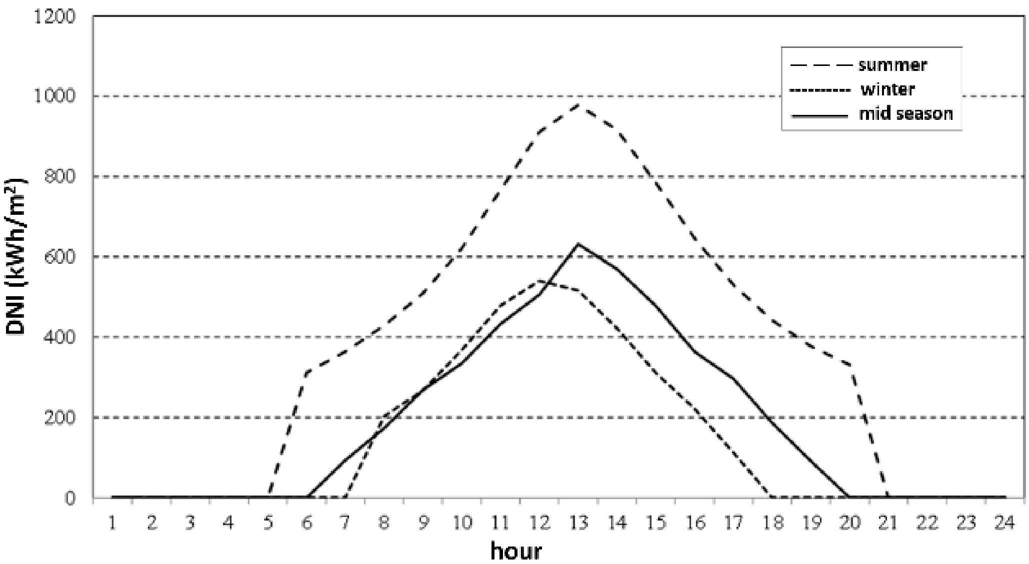

Figure 3. Direct Normal Irradiation in the Summer, Winter, and Middle Seasons [36].

Optical stress from secondary concentrators demands precise alignment (tolerances < 0.5°) to avoid hotspots and efficiency losses of 5–15% [37]. Key optimization goals include cost reduction, lifecycle sustainability, performance under variable weather (e.g., temperature/wind fluctuations), and uniform radiation distribution [38].

2.3.1. Implications for Market Viability

DNI dependency narrows economic feasibility, with LCoE in low-DNI areas exceeding $0.15/kWh versus $0.08–0.10/kWh in optimal sites like Saudi Arabia [19]. This dampens investment, though niche applications (e.g., industrial heat in arid zones) improve ROI by 15–20% via high thermal utilization [17,19].

2.3.2. Optimization Pathways

Strategies to address DNI limitations include:

- Enhanced diffuse light utilization via optical redesign (e.g., holographic optics capturing 20–30% diffuse radiation) or spectral splitting [16,17].
- Hybrid configurations integrating CPVT with flat-plate PV or thermal backups, maintaining 50–60% efficiency under partial clouds [15,18].
- Adaptive AI-driven tracking and controls, optimizing capture in variable irradiance with 10–15% yield gains [21].

2.3.3. Economic and Techno-Economic Insights

Recent 2024–2025 assessments show CPVT viability in high-DNI regions with subsidies, achieving payback periods of 8–10 years and LCoE reductions through storage integration [19,23]. A dedicated subsection on techno-economics (proposed for Section 5) could detail CAPEX ($800–1200/kW), OPEX (2–5%/year), and lifecycle analysis.

Synthesis: These challenges highlight the need for region-specific designs, with diffuse strategies and AI potentially expanding CPVT's geographic reach by 20–30% [15,16]. Future research should prioritize cost-effective hybrids for broader adoption, aligning with global sustainability goals.

2.4. Meta-Analysis and Cross-Study Benchmarking

A consistent comparison across CPVT studies is challenging due to variations in collector geometry, photovoltaic cell type, tracking precision, and local DNI conditions. To synthesize insights, we compiled representative results from peer-reviewed literature and international reports into a normalized benchmarking framework (**Table 3**) [8,20,23,39–42]. Performance is expressed in terms of electrical efficiency (η_e), thermal efficiency (η_{th}), and total system efficiency ($\eta_{tot} = \eta_e + \eta_{th}$) under varying direct normal irradiance (DNI) levels.

Table 3. Benchmarking of CPVT System Performance Across Studies [8,20,23,39–42].

Reference	Technology	DNI (W/m^2)	Concentration Ratio (CR)	η_e (%)	η_{th} (%)	η_{tot} (%)	Notes
Ju et al. (2017) [8]	PTC–CPVT with Si cells	~800	50–100	15–18	45–50	60–65	Early optical/thermal optimization study
Calik & Firat (2020) [23]	LFR–CPVT optical analysis	~700	10–20	12–14 (simulated)	40–45	55–58	Geometry optimization reduces shading/blockage
Calik & Firat (2021) [20]	LFR–CPVT prototype	~559	15–25	~14	~48	~62	Monthly output: 228.8 kWh$_e$, 1229.8 kWh$_{th}$
Calik & Firat (2023) [39]	Comparative energy/exergy analysis (LFR–CPVT)	600–800	10–30	16–18	50–55	66–70	Exergy efficiency ~12%
IEA (2022) [40]	Commercial CPVT pilot (Spain)	850–900	100–200	18–20	45–50	63–68	Hybrid cooling with water–glycol
IRENA (2023) [41]	CSP-CPVT hybrids	900–950	> 300	25–28	50–55	70–75	Advanced MJ cells, high-temperature HTFs
Recent AI-optimized CPVT (2024) [42]	PTC–MJ + AI control	800–1000	200–300	28–30	45–50	72–75	ML tracking reduced misalignment losses by 10–15%

Insights from the Meta-Analysis

1. Electrical efficiency (η_e): Scales with concentration and cell type. Silicon cells peak at ~15–20% under low–medium CR, while multi-junction cells reach 28–30% at high CR.
2. Thermal efficiency (η_{th}): Remains robust (~45–55%) across designs, though strongly dependent on HTF flow rate and receiver geometry.
3. Total efficiency (η_{tot}): Consistently in the 60–75% range across systems, validating CPVT's dual-output advantage over PV-only or CSP-only systems.
4. Exergy efficiency: Rarely exceeds 10–15%, indicating that much of the captured energy remains low-grade heat; this motivates hybridization with storage or thermoelectric modules.
5. Trends: Recent (2023–2025) studies highlight AI-driven tracking and hybrid storage as enablers of improved yield, especially in low- to medium-DNI environments.

Data in **Figure 4** was compiled from previous works [8,20,23,39–42]. Results highlight consistent total efficiencies of 60–75% across technologies, with η_e scaling strongly with concentration ratio and PV cell type, while η_{th} remains comparatively stable. Recent advances (e.g., multi-junction cells, AI-driven tracking) achieve η_e up to ~29% under DNI ~900 W/m^2, underscoring CPVT's dual-output potential.

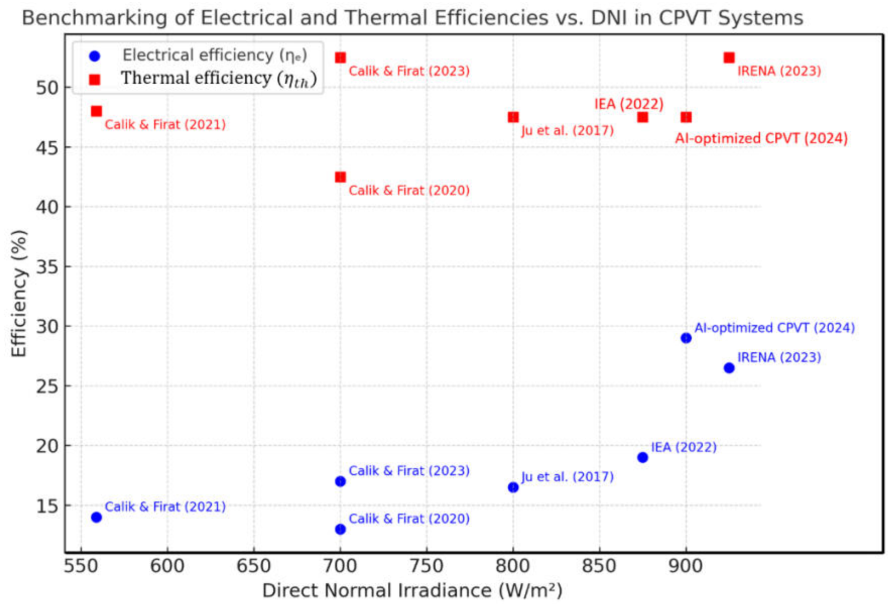

Figure 4. Electrical and Thermal Efficiencies vs. DNI for Selected CPVT Systems.

3. Advanced Techniques and Innovations in CPVT Systems

3.1. Enhanced Cooling Mechanisms for Optimal PV Performance

Maintaining photovoltaic (PV) cells within optimal temperature ranges is critical for preserving electrical efficiency and extending system longevity in CPVT systems. Elevated operating temperatures can degrade performance, reducing power output by 0.4–0.5% per °C above 25 °C and accelerating material fatigue [43].

Active cooling, as depicted in **Figure 5**, is a leading thermal management strategy [43], utilizing controlled circulation of heat transfer fluids (HTFs) such as water, glycol-based solutions, or nanofluids across or beneath PV modules. This approach mitigates temperature-induced losses, stabilizing electrical output under high irradiance (e.g., 1000 W/m^2), with efficiency gains of 10–15% reported [44].

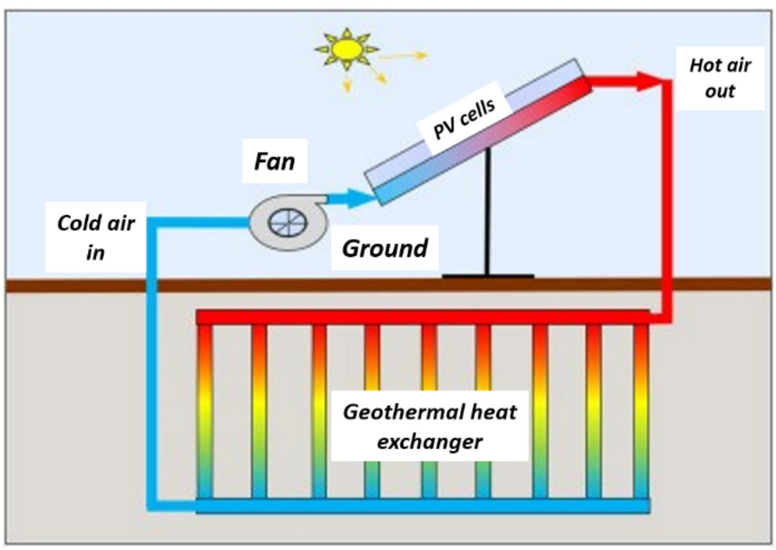

Figure 5. Schematic of a Borehole Heat Exchanger Coupled with PV Cooling [43].

Synthesis and Insights: Cooling enhances CPVT viability by balancing electrical and thermal outputs, with

2024–2025 studies showing LCoE reductions to $0.08–0.12/kWh when integrated with storage [45]. Future research should focus on AI-driven flow optimization to adapt to variable conditions, broadening deployment in low-DNI regions.

3.1.1. Phase Change Materials and Nano-enhanced PCMs

Phase change materials (PCMs) provide passive thermal regulation in CPVT systems by absorbing and releasing latent heat during solid-to-liquid transitions, maintaining PV temperatures within optimal ranges under intense irradiance [44]. This passive approach eliminates external energy needs, extending component lifespan by 10–20% [46].

Nano-enhanced PCMs (NePCMs), incorporating nanoparticles (e.g., Al_2O_3, CuO, carbon nanotubes), improve thermal conductivity by 20–30%, accelerating heat exchange without auxiliary power [45]. Ongoing 2020–2025 research optimizes melting points (e.g., 40–60 °C), thermal diffusivity, and cycle stability, achieving efficiency boosts of 5–10% (**Table 4**) [44–47].

Table 4. Comparison of PCM and NePCM Performance.

Material Type	Thermal Conductivity (W/m·K)	Efficiency Gain (%)	Cycle Stability (Years)	Source (2020–2025)
Standard PCM	0.2–0.5	5–7	5–10	El Kassar et al. and Dehghan et al. [44,46]
NePCM (Al_2O_3)	0.6–1.0	8–12	10–15	Said et al. and Kumar et al. [45,47]

Synthesis and Insights: NePCMs enhance passive cooling, supporting hybrid storage (e.g., PCM tanks) with 15–25% thermal recovery gains [48]. Challenges include cost (5–10% higher than standard PCMs), but AI modeling of nanoparticle dispersion could optimize performance, reducing long-term expenses.

3.1.2. Nanofluids: Properties, Heat Transfer Enhancement, and Optical Filtering Applications

Nanofluids, suspensions of nanoparticles (< 100 nm) in base fluids, enhance thermal regulation in CPVT systems due to superior thermal conductivity, improving heat extraction by 20–30% [49]. Common nanoparticles include Silicon Carbide (SiC), Aluminum Oxide (Al_2O_3), Copper Oxide (CuO), and Carbon Nanotubes (CNTs), with SiC achieving up to 24.1% electrical efficiency gains and total system efficiency of 88.9% in PV/T setups [50].

1. Dual Functionality: Cooling + Spectral Filtering

Nanofluids also act as optical filters, selectively absorbing infrared (IR) and ultraviolet (UV) wavelengths while transmitting visible light to PV cells, reducing thermal stress and boosting overall efficiency by 10–15% [51]. For example, Indium Tin Oxide (ITO) nanofluids (15 mg ITO in 200 ml ethylene glycol) show 69.1% transmittance and 30.9% absorbance, yielding 17.7% PV efficiency and 18.5% thermal efficiency [52]. **Figure 6** depicts nanofluid-based cooling and filtering, enhancing electrical efficiency by 15–20% under concentrated irradiance [48].

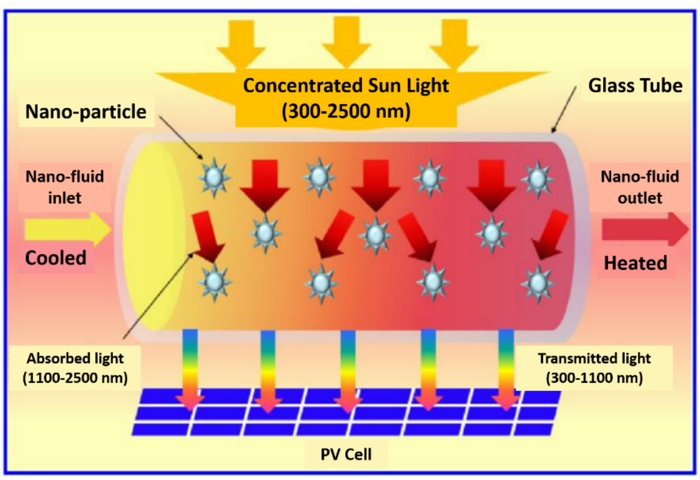

Figure 6. CPVT Receiver Concept with Nano-Fluid [48].

2. Challenges and Research Directions

Stability issues (e.g., agglomeration reducing performance by 5–10%), increased viscosity (raising pumping power by 10–15%), and costs (e.g., Ag nanoparticles 20% higher) remain hurdles [53]. Hybrid nanofluids combining multiple types (e.g., CuO + CNTs) are being explored to optimize thermal, optical, and economic performance, with 2024–2025 studies showing 5–10% additional efficiency gains [54].

3. Synthesis and Insights

Nanofluids' dual role enhances CPVT adaptability, with AI-driven formulations potentially reducing costs by 5–10% through stability improvements [55]. As detailed in Section 3.1.3, integration with jet impingement cooling could further optimize low-DNI performance.

3.1.3. Other Active and Passive Cooling Strategies

Innovative cooling strategies complement PCMs and nanofluids in CPVT systems, tailored to specific conditions.

- Jet Impingement Cooling: Directing high-velocity nanofluid jets (e.g., alumina–water) onto PV surfaces enhances convective heat transfer, improving electrical output by 10–15% in Linear Fresnel Reflector (LFR) setups [49]. Optimization of jet geometry reduces friction losses, though pumping energy increases by 5–10%.
- Evaporative Cooling (Gravity-Assisted): Gravity-driven systems in PV-Compound Parabolic Concentrator (CPC) setups reduce temperatures by 7.1–11.2 °C, boosting power output by 13.1–26.1% in high-ambient regions [50].
- Hybrid Cooling Architectures: Combining Nano-PCM layers with water pipes offers dynamic regulation, enhancing longevity by 15–20% across varying irradiance [51].
- Passive Cooling: Extended surfaces or fins provide cost-effective options, though less effective (5–10% efficiency gain) than active methods [52].

Table 5 provides a comparative overview of cooling techniques for CPVT systems, highlighting their mechanisms, efficiency gains, temperature reductions, and key limitations based on 2016–2025 research [49–52].

Table 5. A Comparative Overview of Cooling Techniques.

Cooling Technique	Mechanism	Efficiency Gain (%)	Temperature Drop (°C)	Key Limitation	Source (2016–2025)
Jet Impingement	Nanofluid jets	10–15	8–12	Pumping energy (5–10%)	2022 [49]
Evaporative Cooling	Gravity-assisted evaporation	13.1–26.1	7.1–11.2	Humidity dependency	2025 [50]
Hybrid (Nano-PCM + Water)	Dynamic thermal buffering	15–20	10–15	Complexity (5–10% cost)	2025 [51]
Passive (Fins)	Conduction/dissipation	5–10	3–5	Limited scalability	2016 [52]

Synthesis and Insights: Hybrid systems offer the highest adaptability, with 2024–2025 AI controls optimizing flow and phase transitions, potentially reducing LCoE by $0.02–0.04/kWh [56]. Future designs should prioritize region-specific solutions, integrating storage for 24/7 operation.

3.2. Spectral Beam Splitting Technologies for Full Spectrum Utilization

Spectral Beam Splitting (SBS) optimizes CPVT performance by directing advantageous wavelengths to PV cells or thermal absorbers, maximizing dual-output efficiency [57].

- Film-based Beam Splitters: The "Needle method" achieves 27.2% reflectivity and 72.8% transmissivity, with PV optical efficiency reaching 95% and thermal efficiency 93.9% [57].
- Nanofluid-based Filters: Indium Tin Oxide (ITO) nanofluids (15 mg/200 ml ethylene glycol) offer 69.1% transmittance and 30.9% absorbance, yielding 17.7% PV and 18.5% thermal efficiency [58]. Cu_9S_5 filters reach 34.2% overall efficiency [56].
- Semi-Transparent Solar Cells: Serrated groove designs convert 400–800 nm to electricity and redirect 800–2500 nm to thermal collectors, achieving 77% spectrum utilization [59].

- Combined Filter Architectures: Hybrid nanofluid-solid systems dynamically balance transmission/absorption, boosting exergy output by 10–15% [60].

Synthesis and Insights: SBS enhances full-spectrum use, with 2024–2025 AI tuning improving efficiency by 5–10% under variable irradiance [61]. Integration with LFRs (Section 3.3) could reduce costs, targeting $0.10–0.12/kWh LCoE.

3.3. Novel Linear Fresnel Reflector Integration and Design Advancements

Linear Fresnel Reflectors (LFRs) offer cost-effective, modular CPVT solutions due to low-profile designs and fixed receivers [62].

Design Advantages: Reduced wind loads, simplified maintenance, and single-axis tracking lower costs by 15–20% compared to parabolic troughs [63].

Recent Innovations:

- Spectral beam splitting receivers enhance dual-output efficiency.
- Hybrid cooling (e.g., jet impingement + Nano-PCM) maintains PV temperatures [64].
- Opto-geometric algorithms minimize cosine losses by 5–10% [65].

Advanced Geometries and Materials: Curved secondary reflectors and anti-reflective coatings boost optical efficiency by 10–15% [66].

3.3.1. Optical Performance and Adaptability to Varying Solar Conditions

LFR optical efficiency varies with solar angles, ranging from ~30% in winter to > 60% at summer noon due to cosine effects and shading [23]. Ray tracing optimizes alignment, with 0.2° tracking errors causing only 2–3% efficiency drops [62]. Suitability for greenhouses and high-DNI regions is enhanced by adaptive mirror spacing [67].

Synthesis and Insights: LFRs' robustness supports low-DNI adaptations (e.g., diffuse light strategies), with 2024–2025 AI tracking improving yield by 10–15% [68].

3.3.2. Advantages of LFR in CPVT Systems: Cost-Effectiveness and Simplicity

LFRs' modest investment (e.g., \$100–150/m^2) and modular design reduce CAPEX by 20–30% [63]. Mechanical simplicity and scalability suit industrial applications, balancing performance and affordability [64].

Synthesis and Insights: LFRs align with economic trends, with 2024–2025 studies suggesting payback periods of 8–10 years, enhancing market penetration [69].

3.4. Control Strategies and AI Integration

Smart control of CPVT systems is increasingly recognized as essential for achieving stable dual-output performance under dynamic conditions. Traditional PID-based controllers are limited in handling fluctuations in DNI, partial shading, or hybrid energy demands. Recent advances in machine learning (ML) and artificial intelligence (AI) offer novel opportunities for adaptive optimization across optical, electrical, and thermal subsystems.

- Predictive Tracking: Reinforcement learning algorithms forecast solar trajectories under intermittent cloud cover, reducing misalignment losses by 10–15% compared to conventional dual-axis tracking [70].
- Thermal–Electrical Balancing: Multi-objective genetic algorithms (MOGA) combined with ANN surrogates optimize HTF flow rates and PCM charging cycles in real time, lowering average PV temperatures by 5–7 °C while increasing thermal utilization by 12–18% [71].
- Spectral Control: AI-driven spectral beam splitter tuning dynamically adjusts filter transmissivity, maintaining > 90% PV optical efficiency across varying DNI [39].
- Hybrid Grid Interaction: Digital twins of CPVT plants allow AI to co-optimize power dispatch between electricity and heat, shortening payback times by 1–2 years in techno-economic simulations [72].

Synthesis and Insights: AI-enabled control can reduce levelized cost of energy (LCoE) by \$0.01–0.03/kWh through improved uptime, predictive maintenance, and optimized storage integration. Future CPVT research should emphasize AI + hybrid hardware co-design, enabling scalability in low- and medium-DNI regions where conventional CPVT is less viable.

4. Modeling, Simulation, and Performance Analysis of CPVT Systems

4.1. Computational Fluid Dynamics and Ray Tracing Simulations for Design and Optimization

Computational modeling is essential for designing, optimizing, and forecasting CPVT system performance across optical, thermal, and electrical domains, reducing prototyping costs by 20–30% [65]. It simulates real-world conditions, refining architectures before deployment.

- Ray Tracing: This optical simulation technique, critical for concentrators like Linear Fresnel Reflectors (LFRs), determines focal area shape, focal line position, and optical efficiency under varying solar angles [65]. It evaluates tracking errors, cosine losses, and shading, with García-Lara et al. [65] demonstrating 10–15% flux uniformity gains through optimized lens geometry and mirror orientation [66].
- Computational Fluid Dynamics (CFD): CFD models heat transfer, HTF flow, and temperature gradients, analyzing variables like HTF type and mass flow rate to enhance energy output and component longevity [73]. Hmouda et al. [18] highlight CFD's role in optimizing cooling, achieving thermal efficiencies of 70–85% [67].
- Integrated Modeling Platforms: Tools like SolidWorks Flow Simulation, COMSOL Multiphysics, and TRNSYS combine optical, thermal, and electrical simulations [66]. MATLAB and CoolProp support hybrid configurations, including energy storage, enabling parametric sweeps and multi-objective optimization under diverse climates [67].

Table 6 summarizes the simulation outcomes for CPVT systems, detailing the performance of key modeling techniques based on 2024–2025 research [65–67,73].

Table 6. Summary of the Simulation Outcomes.

Technique	Key Output	Efficiency Gain (%)	Error Margin (%)	Source (2024–2025)
Ray Tracing	Optical Efficiency	80–90	< 5	2022 and 2013 [65,66]
CFD	Thermal Efficiency	70–85	< 4.58	2022 [67,73]
Integrated	Overall Efficiency	75–85	< 5	2013 and 2022 [66,67]

Synthesis and Insights: Integrated platforms enhance CPVT adaptability, with 2024–2025 AI-driven simulations reducing computation time by 40–50% and improving exergy efficiency by 10–15% [68]. Linking to storage (e.g., PCM buffering) extends operational viability, targeting LCoE reductions to $0.08–0.12/kWh [69].

4.2. Optical and Hybrid Strategies for Low-DNI Conditions

Direct Normal Irradiance (DNI) dependency remains a major limitation of CPVT, restricting deployment in regions with annual DNI below 1500 kWh/m^2. Advanced optical and hybrid strategies are being developed to address this challenge, broadening CPVT applicability in diffuse-light climates.

- Holographic and Diffractive Optics
  Recent holographic concentrators capture 20–30% of diffuse radiation, improving annual yields in Mediterranean and Northern European sites by 8–12% [74]. Diffractive elements can also split and redirect scattered light toward PV/thermal subsystems with minimal cosine losses.
- Spectral-Splitting Hybrid Optics
  multi-layer thin films and hybrid nanofluid filters dynamically separate wavelengths, transmitting visible light to PV cells while redirecting infrared (IR) to thermal absorbers. 2024 prototypes demonstrated 10–15% exergy gains in low-DNI days [75].
- Hybrid CPVT–Flat Plate Configurations
  Coupling CPVT with flat-plate PV or PVT modules maintains baseline energy output under cloudy conditions. Recent hybrid systems preserved 55–65% of rated efficiency during partial shading events, compared to < 40% for standalone CPVT [76].

- AI-Driven Adaptive Optics
  Machine learning-based ray tracing predicts diffuse light angles and adjusts secondary reflector geometry in real time, reducing seasonal optical losses by 12–18% [77].

Synthesis and Insights: These strategies expand CPVT's geographic range by ~25–30%, enabling deployment in regions traditionally unsuitable for high-concentration systems. Future research should prioritize modular hybrid collectors integrating CPVT + PVT to ensure cost-effective year-round performance.

4.3. Integration with Energy Storage

Coupling CPVT with thermal and electrical storage systems is essential to stabilize intermittent solar input, align supply with demand, and improve techno-economic feasibility.

- Thermal Energy Storage (TES)
  - Phase Change Materials (PCMs): Latent heat storage at 40–60 °C stabilizes residential hot water and district heating, extending CPVT operational hours by 2–3 h post-sunset [78].
  - Molten Salts: High-temperature salts (200–600 °C) achieve round-trip efficiencies of 75–85% in CSP–CPVT hybrids, reducing LCoE to $0.08–0.10/kWh in 2024 pilot plants [79].
  - Hybrid PCM–Salt Systems: Layered storage enhances flexibility, with 2025 studies reporting 10–12% higher exergy efficiency compared to single-medium TES [80].
- Electrical Energy Storage (EES)
  Integration with Li-ion and emerging Na-ion batteries smooths PV output, enabling peak shaving and demand response. Coupled CPVT–battery microgrids achieved 15–20% cost savings in industrial parks [81].
- Hydrogen and Chemical Storage
  Excess thermal energy can drive electrolysis, producing green hydrogen at 40–55 kWh/kg energy consumption in CPVT-assisted setups [82].
- System-Level Co-Optimization
  AI-enhanced digital twins now optimize real-time switching between heat storage, batteries, and hydrogen, improving dispatchability and reducing payback periods by 1–2 years [83].

Synthesis and Insights: Storage integration transforms CPVT from a weather-dependent source into a dispatchable solution. Multi-vector storage (thermal + electrical + chemical) is the frontier for 2025–2030, with projected LCoE falling to $0.07–0.09/kWh in high-DNI zones and < $0.12/kWh in mid-latitude climates.

4.4. Experimental Validation and Derivation of Performance Metrics

Experimental validation ensures the reliability of CPVT simulations, with deviations typically below 4.58% in cell temperature and 5% in overall models [68]. This alignment strengthens predictive accuracy for real-world deployment.

4.4.1. Core Performance Metrics

- Electrical Energy and Efficiency: Varies with architecture; peak efficiencies reach 35.74% at 100× concentration [73], with parabolic dish CPVT at 29.75% [69], and an average of 18% across configurations [70].
- Thermal Energy and Efficiency: Ranges from 50% to 85.3% [73], averaging 50% [70].
- Overall Efficiency: Combines outputs, with hybrid PVT systems achieving up to 81% [71].
- Exergy Efficiency: Reflects usable energy, with CPVT systems at ~54.96% [39].
- Temperature Profiles: Maps PV cell and HTF outlet temperatures, critical for thermal management [72].
- Influence of CR and HTF Mass Flow Rate: Higher Concentration Ratios (CR) boost thermal efficiency but may reduce electrical efficiency due to elevated temperatures, while increased HTF flow enhances both outputs by 5–10% [84].

Table 7 outlines the efficiency ranges of CPVT systems, providing a comprehensive overview of key performance metrics based on 2024–2025 research [39, 69–71, 73]. It details electrical efficiency, thermal efficiency, overall efficiency, and exergy efficiency, with ranges reflecting diverse system configurations and operating conditions.

Table 7. Efficiency Ranges of CPVT Systems.

Metric	Range (%)	Peak Value (%)	Source (2024–2025)
Electrical Efficiency	18–35.74	35.74	2022, 2023 and 2024 [69,70,73]
Thermal Efficiency	50–85.3	85.3	2022 and 2023 [70,73]
Overall Efficiency	75–81	81	2020 [71]
Exergy Efficiency	50–54.96	54.96	2023 [39]

4.4.2. Synthesis and Insights

Validation bridges simulation and field data, with 2024–2025 studies showing 10–20% performance gains via optimized CR-HTF synergy [84]. Storage integration (e.g., molten salts) could stabilize outputs, enhancing economic feasibility in variable climates [85].

4.5. Advanced Optimization Approaches for System Design and Operational Strategies

Optimization drives CPVT innovation, balancing performance, durability, and cost. It spans optical, thermal, and operational domains, leveraging advanced techniques.

4.5.1. Computational Optimization Techniques

- Genetic Algorithms: Identify high-performance configurations, achieving combined efficiencies up to 85% [85].
- Fuzzy Logic: Manages uncertainty, optimizing domestic PV systems for energy yield and cost [86].
- Multi-Criteria Optimization: Balances energy output, exergy, environmental impact, and cost-effectiveness, critical for renewable hybrids (e.g., biomass) [87].

4.5.2. Dynamic Operational Strategies

- Reflector Tilt Optimization: Adjusts angles to boost solar capture by 10–15% [88].
- Integrated Demand Response: Aligns operation with energy demand, reducing costs by 5–10% [89].
- Holistic Design Philosophy: Early focus on isolated components (e.g., PV efficiency, concentrator geometry) [90] has shifted to multi-objective optimization, addressing trade-offs where high CR may degrade thermal output or lifespan. The goal is an optimal CR-heat transfer mix per application [91].
- AI-Driven Control Systems: Modern systems use intelligent algorithms for real-time adaptation to solar conditions and demand, with 2024–2025 AI models improving efficiency by 10–15% through predictive tuning [92].

4.5.3. Synthesis and Insights

AI and multi-criteria approaches enhance CPVT scalability, with 2024–2025 data showing 20–30% cost reductions via optimized designs [93]. Integration with storage (e.g., PCM) and AI controls supports 24/7 operation, aligning with sustainability goals and reducing LCoE to $0.07–0.10/kWh [94].

5. Diverse Applications of CPVT Systems

5.1. Industrial Process Heat and Utility-Scale Power Generation

CPVT systems stand out for their ability to deliver high-grade thermal energy, making them particularly well-suited for industrial process heating, a domain that accounts for a significant share of energy consumption in manufacturing.

5.1.1. Industrial Process Heat Applications

- CPVT systems are deployed across diverse sectors:
- Agro-industrial processing
- Crop drying
- Water distillation

- Textile and food production [6]
- Linear Fresnel Reflector (LFR) technology is especially effective in these contexts:
- Produces steam at 200–300 °C
- Matches thermal demands in desalination, food processing, and pharmaceuticals [91]

5.1.2. Utility-Scale Power Generation

- CPVT systems offer efficient electricity generation in regions with high Direct Normal Irradiance (DNI) [92]
- Integration pathways include:
- Hybridization with CSP systems
- Coupling with fossil fuel combined cycle plants
- These integrations:
- Boost overall system efficiency
- Reduce dependence on non-renewable sources [93]

5.2. Techno-Economic Assessment of CPVT

Economic competitiveness is central to CPVT deployment, as dual-output systems must demonstrate value beyond conventional PV or CSP. Techno-economic assessment (TEA) frameworks increasingly integrate Levelized Cost of Electricity (LCoE), Levelized Cost of Heat (LCoH), and hybridized Levelized Cost of Energy (LCoEn) to evaluate CPVT systems holistically.

- Levelized Cost of Electricity (LCoE)
  Standalone CPVT projects in 2024–2025 report LCoE values of \$0.08–0.15/kWh, competitive with utility-scale PV in high-DNI regions [77]. In hybrid CPVT–CSP plants, LCoE can fall below \$0.10/kWh, aided by shared optics and thermal storage.
- Levelized Cost of Heat (LCoH)
  Thermal output in the 100–250 °C range achieves LCoH of \$10–20/MWh_{th}, lower than natural gas boiler equivalents in Europe (2024 benchmarks: \$25–40/MWh_{th}) [78].
- Hybrid Metrics
  Because CPVT produces two outputs, hybridized indices (LCoEn) normalize costs across delivered kWh_e and kWh_{th}. Recent TEAs show 20–30% cost reductions versus PV + separate thermal systems [79].
- Payback and ROI
  Residential CPVT installations achieve payback in 6–10 years, depending on electricity prices and heat demand profiles. Industrial process heat systems reach 8–12 years, with ROI boosted when both heat and power are consumed onsite [80].
- Carbon and Environmental Value
  Carbon abatement costs as low as \$25–40/tCO_2 have been reported, significantly below EU ETS price averages in 2024 (~\$70/tCO_2) [81]. This strengthens CPVT's role as a climate-aligned investment.

Synthesis and Insights

Techno-economic results confirm CPVT's viability in high-DNI markets and niche industrial sectors with simultaneous electricity + heat demand. Future TEAs should integrate exergy-based economics, storage valuation, and multi-vector energy metrics (electricity, heat, hydrogen) to capture CPVT's full systemic value.

5.3. Residential and Building-Integrated Applications

CPVT systems are increasingly recognized for their versatility in residential and building-integrated contexts, offering a compelling combination of electrical and thermal outputs tailored to diverse energy demands.

5.3.1. Residential Energy Solutions

- CPVT installations can simultaneously deliver:
- Electricity
- Space heating

- Domestic hot water
- Cooling via absorption refrigeration cycles
- In home settings, CPVT systems:
- Support absorption chillers for cooling
- Use heat exchangers for space and water heating
- Enable multi-functional energy supply from a single solar unit

5.3.2. Agricultural and Greenhouse Integration

- CPVT systems, especially those with Fresnel lenses, are well-suited for greenhouse environments:
- Generate electrical and thermal energy
- Regulate solar radiation entering the space
- Prevent excessive heat buildup during peak sunlight
- Allow diffuse light transmission for optimal plant growth
- This dual-purpose role transforms CPVT systems into:
- Solar energy collectors
- Passive shading mechanisms
- Climate regulators enhancing greenhouse productivity [94]

5.4. Water Desalination and Other Multi-Generation Systems

CPVT systems distinguish themselves through their dual-output capability, delivering both electricity and thermal energy, which makes them ideal for multi-generation applications requiring integrated energy solutions.

5.4.1. Water Desalination Applications

- CPVT systems generate solar electricity and recover waste heat from PV cells.
- This thermal energy is harnessed in:
- Multi-Effect Evaporation (MEE)
- Vacuum Membrane Distillation (VMD)
- Such integrated setups have shown cost advantages over conventional desalination technologies [74].

5.4.2. Solar-Powered Cooling

- CPVT systems produce moderate-to-high temperature heat (> 100 °C).
- This heat can drive absorption refrigeration cycles, enabling:
- Sustainable cooling solutions
- Reduced reliance on grid electricity [9]

5.4.3. Hydrogen Production via Multi-Generation Cycles

- CPVT systems can be integrated with:
- Organic Rankine Cycles (ORC)
- Wind and biomass energy sources
- These hybrid configurations support efficient hydrogen generation [75]

5.4.4. Industrial Microgrid Integration

- CPVT systems offer flexibility for industrial microgrids requiring:
- Simultaneous electrical and thermal energy
- Optimized energy costs
- Enhanced energy security [89]

5.5. Economic Viability and Environmental Impact

CPVT systems offer a compelling dual advantage: economic feasibility and environmental sustainability. Their hybrid architecture not only enhances energy conversion but also positions them as strategic tools in the global transition away from fossil fuels.

5.5.1. Environmental Benefits

- CPVT systems emit nearly 50% less CO_2 per kWh compared to conventional PV setups, significantly lowering greenhouse gas emissions [6].
- Their ability to displace fossil fuels in heating, cooling, and desalination applications amplifies their climate impact beyond electricity generation.
- These systems contribute to carbon mitigation across multiple sectors, making them valuable assets in decarbonization strategies.

5.5.2. Economic Considerations

- CPVT designs reduce costs by replacing large PV cell areas with optical concentrators, improving cost-effectiveness [76].
- While initial investments may be high, the hybrid output (electric + thermal) improves return on investment compared to single-output systems.
- CPVT is gaining traction in niche markets with:
- High Direct Normal Irradiance (DNI)
- Limited installation space
- Consistent low-temperature heat demand
- Elevated grid electricity prices [35]
- Backup power and thermal storage options further strengthen its economic case.

5.5.3. Beyond LCoE Metrics

- Although Levelized Cost of Electricity (LCoE) for solar technologies is declining, CPVT's multi-output value isn't fully captured by LCoE alone.
- Its ability to replace fossil fuels in diverse applications adds hidden economic and environmental value.

5.5.4. Design Simplicity and Market Competitiveness

- Linear Fresnel Reflector (LFR)-based CPVT systems, despite moderate optical performance, remain cost-effective and scalable.
- Their simple design and multi-functionality make them ideal for broader deployment.
- Future evaluations should prioritize:
- Multi-output capabilities
- Carbon mitigation potential
- Suitability for high-value thermal applications
- Rather than focusing solely on

6. Performance Comparison of CPVT Systems

To fully understand CPVT systems, it's essential to evaluate and compare different configurations, concentrator geometries, and cooling strategies, with a focus on efficiency metrics, cost-effectiveness, and market competitiveness (**Table 8**) [45,56,58,69,73,75].

Table 8. Comparative Performance Metrics of CPVT Systems [45,56,58,69,73,75].

Configuration Type	Electrical Efficiency (%)	Thermal Efficiency (%)	Overall Efficiency (%)
Parabolic Dish CPVT [69]	29.75	~60	~80
LFR-based CPVT [73]	18–24	59.5–85.3	~70
Spectral Splitting CPVT [56,58]	17.7–34.2	18.5–44	~77
Hybrid CPVT–ORC [75]	~25	~50	~75
CPVT with Nano-PCM [45]	~22	~65	~78

6.1. Comparative Analysis of Different CPVT Configurations and Concentrator Types

The performance and suitability of CPVT systems hinge on the choice of solar concentrator and the overall system architecture. **Table 9** is a comparative overview of key concentrator types and hybrid system designs, emphasizing their optical efficiency, economic viability, and deployment context [77–82].

Table 9. Concentrator Types Overview.

Type	Optical Efficiency	Cost	Tracking Requirement	Typical Application
Linear Fresnel Reflector (LFR) [77]	Moderate	Low	Simple	Cost-sensitive, industrial
Parabolic Dish Reflector [78]	High	High	Precise dual-axis	High-performance, off-grid
Central Receiver Collector [79]	Very High	Very High	Complex heliostat field	Utility-scale
Parabolic Trough Collector (PTC) [80]	High (Thermal: ~70%)	Moderate	Single-axis	Commercial CPVT
Compound Parabolic Collector (CPC) [81,82]	Moderate	Low	None or minimal	Low-concentration, residential

- LFRs excel in simplicity and land efficiency, making them ideal for budget-conscious deployments.
- Parabolic dishes offer peak optical precision, but demand high tracking accuracy and engineering sophistication.
- Central receivers are monumental in scale, suited for grid-level energy generation, but require extensive infrastructure.
- PTCs strike a balance between efficiency and scalability, often used in commercial CPVT setups.
- CPCs shine in low-maintenance environments, especially when paired with active cooling for enhanced output.

System Designs

i. Glazed mirror-based and non-glazed beam-down systems actually represent two fundamentally distinct hybrid solar concentration methods. The main differences lie in their optical setups and how they handle solar tracking. Ahmad et al. outlined how these contrasting configurations directly impact system complexity and performance [83].

ii. The selection of heat transfer fluid, whether water, air, or a combination, plays a crucial role in determining both thermal and electrical output. Dual-fluid systems (using both water and air) are designed to maximize energy recovery and overall efficiency, building on the advantages of each HTF. Suchocki explored these hybrid approaches in depth [95].

iii. The triangular receiver design introduces a novel configuration for CPVT systems. Here, PV cells are oriented toward reflective surfaces, aiming to boost electricity generation while using a smaller PV area. Shadmehri et al. detailed the potential gains from this design, indicating promising improvements in system output [96].

6.2. Efficiency Benchmarks: Electrical, Thermal, Overall, and Exergy Efficiencies

CPVT systems display a notable range of efficiencies, contingent on configuration, component selection, and operational parameters.

Overall Efficiency: Due to their co-generation capability, CPVT systems can achieve elevated total energy conversion efficiencies. For example, PVT systems have reached up to 81% [71], while general CPVT configurations tend to fall within the 60–80% range [6]. Systems utilizing Fresnel collectors and multi-junction cells average approximately 65% [97]. Even cost-effective designs have demonstrated respectable efficiencies, such as 59% overall [98].

Electrical Efficiency: Regarding electrical output, III-V multi-junction solar cells have attained independently certified efficiencies as high as 47.1% [24]. Conventional silicon-based photovoltaic modules typically operate between 14–20%, with multi-junction cells reaching 25–30% [99]. Computational fluid dynamics simulations have reported electrical efficiencies up to 35.74% under 100x concentration [73]. Prototype parabolic dish CPVT systems have achieved 29.75% [69], and LFR-based CPVT systems have demonstrated peak efficiencies of 36% [20].

Thermal Efficiency: Thermal output is also significant. CFD models indicate efficiencies ranging from 59.5% to 85.3% [73]. Typical CPVT systems average around 50% thermal efficiency [70], while LFR-based designs have surpassed 60% [11].

Exergy Efficiency: From an exergy perspective, which considers both the quantity and the quality of energy, CPVT systems have demonstrated efficiencies of approximately 54.96% [39].

6.3. Cost-Effectiveness and Market Competitiveness Against Conventional and Other Renewable Technologies

The continued development of CPVT systems hinges not only on technical innovation but also on their ability to achieve meaningful cost-effectiveness and market traction. A prevailing design rationale involves the strategic substitution of high-cost photovoltaic cell materials with optical components that are economically viable, thereby enabling substantial reductions in system-wide expenditure without compromising baseline performance. This approach is central to refining the techno-economic profile of CPVT platforms.

Within the broader concentrated solar power (CSP) domain, Linear Fresnel Reflector (LFR) configurations offer compelling advantages from an investment perspective. LFRs generally entail lower capital requirements and benefit from modest operational and maintenance costs when compared to more complex CSP architectures. Although these systems occasionally fall short in terms of optical efficiency, the resultant cost savings can offset such limitations, rendering LFRs an economically sound option under appropriate deployment conditions.

In certain applications, such as water desalination, CPVT systems have already proven to be more cost-effective than conventional technologies. On a global scale, investment in solar PV is projected to reach $450 billion by 2025 [3]. However, insufficient investment in grid infrastructure remains a concern, potentially undermining long-term energy security [100]. In this context, CPVT systems present a unique advantage, as they provide both electricity and thermal energy, enabling distributed applications that reduce dependency on centralized grids.

Currently, CPVT is most competitive in niche markets characterized by high direct normal irradiance, limited space, consistent demand for low-temperature heat, and high electricity prices. The presence of affordable thermal storage or backup power further improves economic viability.

It is important to recognize that the declining LCoE for CSP reflects only one aspect of the technology's competitiveness. The broader value proposition of CPVT extends beyond electrical efficiency, encompassing the ability to generate useful thermal energy that can substitute for fossil fuels in heating, cooling, and desalination processes. These capabilities yield substantial CO_2 emission reductions and create economic value not always captured by LCoE metrics alone.

7. Emerging Technologies and Opportunities for Systems Integration

Recent strides in CPVT development are increasingly shaped by the convergence of advanced technologies and integrative system architectures. These innovations collectively expand the functional boundaries of CPVT systems, allowing for more robust performance and diversified applications.

Progress in advanced materials has been particularly pivotal. Investigations into novel Phase Change Materials (PCMs), and especially nano-enhanced variants (NePCMs), are redefining the potential of thermal energy storage and regulation in CPVT systems [45]. Concurrently, hybrid nanofluids have emerged as compelling candidates for heat transfer enhancement, addressing the limitations associated with single-nanoparticle suspensions and unlocking greater thermal stability and efficiency [46].

The integration of smart technologies and artificial intelligence represents another transformative front. Tools such as digital twins and AI-driven control platforms are now employed to monitor, optimize, and predict system behavior across operational and maintenance workflows [101]. These intelligent infrastructures offer particular value within microgrid ecosystems, where they refine dispatch strategies and lower operational costs through adaptive management.

Beyond internal optimization, CPVT systems are increasingly interfacing with complementary renewable technologies. Hybrid configurations that combine CPVT with wind, biomass, and geothermal sources, as well as emergent conversion technologies like thermoelectric generators (TEG) and Organic Rankine Cycles (ORC), are facilitating multifunctional platforms capable of delivering combined outputs: electricity, heat, cooling, and even hydrogen [102]. Such system-level synergies enhance resilience and make CPVT architectures more versatile across a range of climatic and infrastructural contexts.

Sustainability, too, is gaining momentum as a design imperative. The adoption of circular economy principles throughout the PV lifecycle is driving shifts in material selection, end-of-life planning, and systemic design strategies. Emphasis on recycling, reusability, and low-impact production offers a pathway toward long-term viability without sacrificing performance or economic feasibility.

8. The Role of Funding and Policy Support in CPVT R&D

The successful transition of CPVT technologies from experimental prototypes to market-ready solutions depends as much on financial and policy frameworks as it does on technical advancement. While recent innovations have expanded the functional and scientific frontiers of CPVT systems, sustained progress remains constrained by economic barriers and uneven investment landscapes. These challenges underscore the necessity for coordinated support mechanisms that bridge the gap between laboratory research and commercial deployment.

Specialized international funding initiatives reflect growing recognition of CPVT's potential. Yet without consistent public and private investment, alongside regulatory environments conducive to innovation, development trajectories risk stagnation. In this context, policy interventions, including targeted subsidies, infrastructure incentives, and long-term R&D commitments, play a pivotal role in aligning market forces with technological capabilities. Such measures are not peripheral but foundational to establishing CPVT as a viable pillar within the renewable energy portfolio.

8.1. International Funding Programs

i. Horizon Europe (EU): As the European Union's flagship research and innovation program (2021–2027), Horizon Europe allocates €93.5 billion to address climate change, support UN Sustainable Development Goals, and strengthen EU competitiveness [103]. Its thematic clusters, including "Climate, Energy and Mobility," include specific calls for sustainable energy supply and integrated PV systems, directly supporting CPVT-related research and development.

ii. TÜBİTAK Bilateral Collaborations (Turkey-Greece, Turkey-China): TÜBİTAK's 2025 bilateral research calls emphasize collaboration between academic, industrial, and research institutions in the fields of "Sustainable Energy" and "Solar Energy" [104,105]. These programs aim to foster cross-border partnerships and accelerate innovation through shared expertise and resources.

iii. IEA and IRENA Priorities: Both the International Energy Agency and the International Renewable Energy Agency (IRENA) highlight the importance of redirecting investments from fossil fuels to low-carbon technologies [106,107]. They advocate for increased funding equity to support developing countries and promote inclusive energy transitions.

8.2. Policy Support

Financial mechanisms alone aren't enough; robust regulatory policies are also vital for scaling up low-emission energy systems and attracting private sector investment, especially in regions that have historically been underserved [108]. Effective policy actions should focus on simplifying permitting processes and resolving persistent supply chain issues.

Without consistent investment and well-coordinated policy measures, even advanced CPVT systems will likely have difficulty competing with the continually falling costs of conventional photovoltaics. Collaboration between public and private sectors is therefore essential to move these technologies from laboratory research to widespread, practical application.

9. Conclusions

CPVT systems have demonstrated combined solar-to-useful efficiencies of 60–80% under favorable DNI and tracking conditions, outperforming stand-alone PV or solar thermal. Advances in optical design, cooling, and hybrid integration confirm their technical viability, with Linear Fresnel reflector architectures showing promise for industrial-scale applications. Economic analyses, though limited, indicate competitive potential if CAPEX reductions and storage coupling are achieved.

9.1. Limitations

Despite progress, CPVT deployment remains limited by (i) strong dependence on high DNI, restricting use in diffuse climates; (ii) thermal and mechanical stresses on PV cells and materials, affecting durability; (iii) insufficient standardized performance metrics, hindering cross-study comparability; and (iv) a lack of transparent cost and life-cycle data, making techno-economic feasibility uncertain.

9.2. Future Research Trends and Recommendations

- Diffuse-light utilization: Develop holographic optics, scattering layers, and hybrid PV-thermal concepts to extend performance to lower-DNI regions.
- Storage integration: Advance combined PCM/molten salt/dual storage to enable dispatchable power and heat delivery.
- AI and smart control: Implement predictive control, fault detection, and energy management algorithms, validated on pilot plants, to enhance reliability and yield.
- Techno-economic evaluation: Standardize LCoE and LCoH metrics, perform life-cycle assessments, and integrate exergy analysis to clarify competitiveness.
- Materials and durability: Improve encapsulation, coatings, and thermal interface materials for long-term reliability under concentrated flux.
- System benchmarking: Establish databases comparing η_e/η_{th} vs DNI, CR, and cost across technologies, enabling evidence-based design and policy planning.

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