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Mathematical Modeling and Optimization of Photovoltaic–Phase Change Material Cooling Systems for Enhanced Thermal Management in Public Electric Vehicle Charging Stations

Zainal Arifin[1*], Singgih Dwi Prasetyo[2], Chico Hermanu Brillianto Apribowo[3], Dominicus Danardono Dwi Prija Tjahjana[1], Yuki Trisnoaji[2], Noval Fattah Alfaiz[1], Watuhumalang Bhre Bangun[1]

[1] Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia
[2] Power Plant Engineering Technology, State University of Malang, Malang 65145, Indonesia
[3] Department of Electrical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia

Corresponding Author Email: zainal_arifin@staff.uns.ac.id

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ABSTRACT

This manuscript presents a detailed examination of mathematical modeling and optimization of photovoltaic–phase change material (PV-PCM) cooling systems tailored explicitly for public electric vehicle (EV) charging stations. Effective thermal management has become crucial to maintain optimal efficiency and performance with the increasing deployment of solar PV technologies and the simultaneous rise in EV infrastructure. The research highlights the significant negative impact of high operating temperatures on PV panel output, establishing the need for efficient cooling solutions. The study employs a systematic review methodology, synthesizing recent literature published over the last five years. It draws upon numerical modeling, experimental validation, and thermodynamic principles to analyze and optimize PV-PCM systems in various climatic scenarios. Key aspects such as material selection, thermal performance characteristics, system design configurations, and integration with active cooling methods are critically evaluated. Findings indicate that while many studies have explored PV-PCM systems, there remains a substantial gap in focusing on the unique operational demands of public EV charging stations. The analysis reveals a variety of PCM materials with differing thermal properties, alongside innovative cooling configurations that could enhance system efficiency. Additionally, integrating these systems with existing technologies is discussed, providing valuable insights into optimizing thermal management for improved PV output. This review is a foundational resource to bridge knowledge gaps, offering recommendations for future research and practical applications in EV charging infrastructure. Consolidating fragmented research aims to contribute to advancing sustainable energy solutions in the context of electric mobility.

1. INTRODUCTION

Research on mathematical modeling of photovoltaic–phase change material (PV-PCM) cooling systems for public electric vehicle (EV) charging stations has emerged as a critical area of inquiry due to the increasing demand for efficient renewable energy integration and thermal management in solar photovoltaic (PV) technologies [1, 2]. Over the past decade, PV systems have seen rapid growth, with annual installation rates exceeding 30%, driven by the need to reduce fossil fuel dependence and environmental impacts [3, 4]. However, the efficiency of PV panels is significantly compromised by elevated operating temperatures, which can reduce electrical output by up to 0.65% per degree Celsius increase [5, 6]. The integration of phase change materials (PCMs) as passive cooling agents has evolved as a promising solution, enhancing thermal regulation and extending system lifespan [7, 8]. This field has progressed from basic experimental setups to sophisticated numerical and optimization models that consider climatic variations and material properties [9, 10].

Despite advances, the specific application of PV-PCM cooling systems tailored for public EV charging stations remains underexplored, presenting a notable knowledge gap [11, 12]. While numerous studies have modeled PV-PCM systems under diverse environmental conditions, few have addressed the unique thermal and operational demands of EV charging infrastructure [13-15]. Controversies persist regarding the optimal PCM selection, system configuration, and integration with active cooling methods, with some research advocating hybrid approaches combining PCMs with fluid cooling or thermoelectric generators [13, 16, 17]. In contrast, others emphasize purely passive systems for cost-effectiveness [18]. The absence of consensus on these aspects limits the deployment of efficient, scalable cooling solutions for EV charging stations, potentially affecting energy efficiency and system reliability [19].

The conceptual framework underpinning this review defines PV-PCM systems as hybrid modules where PCMs absorb and store latent heat to regulate PV cell temperatures, thereby enhancing electrical efficiency [2]. Mathematical modeling serves as a tool to simulate heat transfer dynamics, phase transitions, and system performance under varying climatic and operational parameters [20]. This framework links thermal management strategies with energy output optimization, guiding the selection and design of PV-PCM cooling systems for EV charging applications [8].

This systematic review aims to critically analyze and synthesize recent mathematical modeling approaches of PV-PCM cooling systems, focusing on their applicability to public EV charging stations. This review aims to bridge the identified knowledge gap by evaluating PCM materials, cooling configurations, and modeling techniques, thereby providing insights to optimize thermal management and improve PV system efficiency in EV infrastructure [21, 22]. The value added lies in consolidating fragmented research and highlighting design considerations specific to EV charging contexts.

This review employs a comprehensive literature survey of peer-reviewed studies published in the last five years, emphasizing numerical modeling and experimental validation of PV-PCM systems. Inclusion criteria focus on studies addressing thermal performance, PCM characterization, and system optimization relevant to PV cooling. Analytical frameworks include thermodynamic modeling, computational fluid dynamics, and multi-objective optimization methods. The findings are organized to discuss material selection, system design, climatic influences, and integration strategies, culminating in recommendations for future research and practical implementation [23, 24].

The novelty of this review lies in its explicit focus on photovoltaic–phase change material (PV–PCM) systems designed for public EV charging stations, a context rarely addressed in previous reviews. While earlier works have generally examined PCM integration in PV systems for residential or general renewable energy applications, this study emphasizes the distinct operational, spatial, and thermal management challenges inherent in EV charging infrastructure. By systematically consolidating recent studies, this review uniquely highlights the trade-offs, performance gaps, and optimization approaches specific to public EV stations. Furthermore, unlike prior reviews on material properties or laboratory-scale validation, this paper integrates perspectives on system-level feasibility, economic considerations, and policy relevance. This targeted scope ensures that the findings contribute to theoretical understanding and practical deployment in sustainable mobility infrastructure.

2. PURPOSE AND SCOPE OF THE REVIEW

2.1 Statement of purpose

The objective of this report is to examine the existing research on "Mathematical Modeling of Photovoltaic–phase change material cooling systems for Public EV Charging Stations" to synthesize current knowledge on the integration of phase change materials (PCMs) with photovoltaic (PV) systems for thermal management and efficiency enhancement. This review is essential because the rising demand for sustainable energy solutions in electric vehicle (EV) infrastructure necessitates optimized cooling strategies to maintain PV performance under varying environmental conditions. By analyzing mathematical models and experimental validations, the report aims to identify effective cooling mechanisms, evaluate the impact of PCMs on PV temperature regulation, and explore their applicability in public EV charging stations. The findings will guide future research and practical implementations that enhance energy efficiency and reliability in renewable energy systems supporting EV infrastructure.

2.2 Specific objectives

Building upon the identified research problem and overarching aim, the study is structured around specific objectives designed to guide the investigation systematically. These objectives are outlined as follows:

- To evaluate current knowledge on mathematical modeling techniques for PV-PCM cooling systems in renewable energy applications.
- Benchmarking existing thermal management approaches in photovoltaic systems integrated with phase change materials.
- Identification and synthesis of key parameters influencing the performance of PV-PCM cooling systems under diverse climatic conditions.
- To compare the effectiveness of different phase change materials and hybrid cooling configurations in reducing PV operating temperatures.
- To deconstruct challenges and opportunities in applying PV-PCM cooling technologies specifically for public electric vehicle charging stations.

3. METHODOLOGY OF LITERATURE SELECTION

3.1 Transformation of query

We expand your original research question — "Mathematical Modeling of Photovoltaic–Phase Change Material Cooling Systems for Public EV Charging Stations"— into multiple, more specific search statements. By systematically expanding a broad research question into several targeted queries, we ensure that your literature search is comprehensive (you won't miss niche or jargon-specific studies) and manageable (each query returns a set of papers tightly aligned with a particular facet of your topic). Below were the transformed queries we formed from the original query:

- Mathematical modeling of photovoltaic–phase change material cooling systems for public EV charging stations.
- Exploring advanced cooling techniques for photovoltaic systems in electric vehicle applications using various phase change materials and their impact on energy efficiency and temperature management.
- Investigating the integration of nanofluids with phase change materials in photovoltaic cooling systems for improved energy efficiency and thermal management in electric vehicle applications.
- Exploring synergistic effects of novel nanofluids and phase change materials in enhancing the efficiency of photovoltaic thermal systems for electric vehicle charging applications.

- Investigating innovative designs and applications of hybrid photovoltaic thermal systems utilizing advanced cooling techniques, including phase change materials and nanofluids, for improved energy efficiency in electric vehicle charging stations.

3.2 Identifying and applying inclusion and exclusion criteria

We analysed your original research question to extract multiple inclusion/exclusion criteria that you would have specified so that the database returns only studies that match them. Below were the identified Inclusion-Exclusion Criteria:

- Papers up to the year 2024.
- Include keywords related to Indonesian Renewable Energy Regulations, Presidential Regulation 112/2022, Minister of Energy and Mineral Resources Regulation 1/2023, and Minister of Energy and Mineral Resources Regulation 2/2024.

3.3 Screening papers

We then run each of your transformed queries with the applied Inclusion & Exclusion Criteria to retrieve a focused set of candidate papers for our constantly expanding database of over 270 million research papers. during this process we found 236 papers. Citation Chaining - Identifying additional relevant works:

- **Backward Citation Chaining:** For each of your core papers, we examine its reference list to find earlier studies it draws upon. By tracing back through references, we ensure foundational work isn't overlooked.
- **Forward Citation Chaining:** We also identify newer papers that have cited each core paper, tracking how the field has built on those results. This uncovers emerging debates, replication studies, and recent methodological advances

A total of 64 additional papers were found during this process.

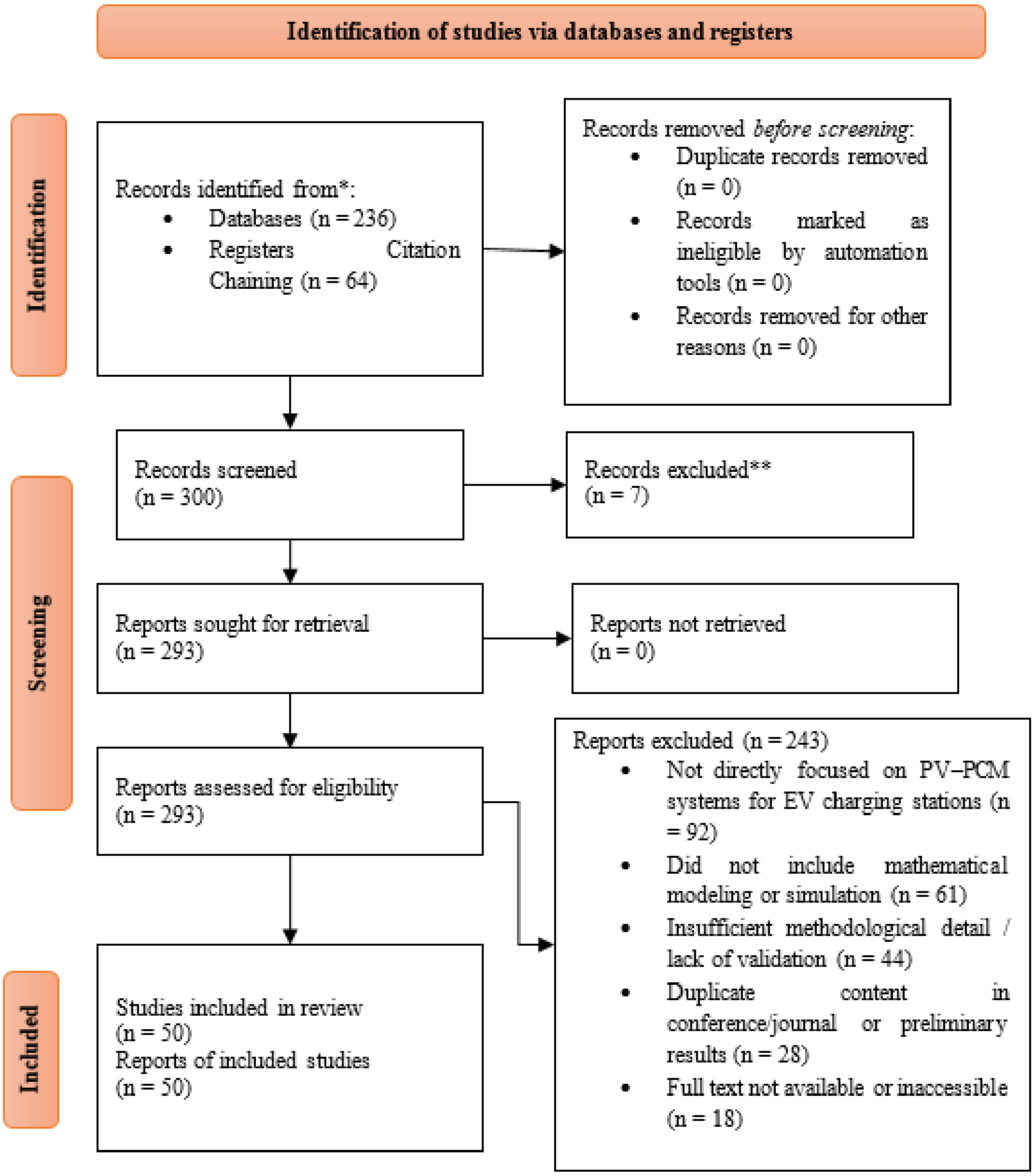

Figure 1. PRISMA flow diagram of the literature selection process

3.4 Relevance scoring and sorting

We take our assembled pool of 300 candidate papers (236 from search queries + 64 from citation chaining) and impose a relevance ranking so that the most pertinent studies reach the top of our final papers table. We found 300 papers that were relevant to the research query. During the screening stage, seven papers were excluded because they were identified as unrelated to the topic based on title and abstract evaluation, leaving 293 papers for full-text assessment. Out of 293 papers, 243 were further excluded for the following reasons: 92 papers did not directly focus on PV–PCM systems for EV charging stations, 61 papers did not include mathematical modeling or simulation, 44 papers lacked sufficient methodological details or proper validation, 28 papers were duplicate publications appearing in both conference and journal formats, and 18 papers were not accessible in full text. After this rigorous screening, 50 papers were selected as highly relevant and included in the final synthesis. Figure 1 illustrates the PRISMA Flow Diagram of the Literature Selection Process, which now reflects the complete inclusion and exclusion steps.

4. RESULTS

4.1 Descriptive summary of the studies

The reviewed literature indicates that photovoltaic–phase change material (PV–PCM) cooling systems have substantially improved thermal regulation and energy efficiency across diverse studies. Reported results highlight that PV operating temperatures can be reduced by approximately 5°C to more than 27°C, depending on the PCM properties, system configuration, and climatic conditions [1]. These reductions translate into notable electrical efficiency gains ranging from 2% to over 30%, while advanced designs such as hybrid systems with nano-enhanced PCMs achieve even greater improvements [24, 25]. Modeling accuracy has been enhanced using computational fluid dynamics (CFD), MATLAB-based optimization, and transient models, many of which are validated against experimental data. Collectively, these findings reinforce the capability of PV–PCM systems to mitigate overheating, increase energy yield, and provide a stronger foundation for integration into renewable energy infrastructures [7, 21].

At the same time, the synthesis reveals that system performance is highly dependent on environmental adaptability, with consistently better outcomes in hot and high-irradiance climates compared to colder regions. Passive PCM cooling designs are generally scalable and cost-effective, making them attractive for large-scale applications. In contrast, hybrid methods that combine PCMs with nanofluids, fins, or thermoelectric generators provide higher efficiency but involve more complexity and investment. Studies further show that economic feasibility varies with local conditions, with some systems achieving favorable payback periods while others face cost barriers due to advanced material requirements. Another recurring insight is the need for improved long-term durability of PCMs, as cyclic thermal loading may affect stability and efficiency over time. To provide a structured overview of these insights, **Appendix 1** summarizes the descriptive findings of the reviewed studies, focusing on modeling accuracy, thermal performance, energy efficiency improvements, environmental adaptability, and system integration feasibility.

4.1.1 Modeling accuracy

The reviewed literature demonstrates notable progress in improving the accuracy of mathematical models for PV–PCM cooling systems. Several studies provide strong validation and employ advanced modeling techniques, as summarized below:

- 15 studies demonstrated strong validation of mathematical models with experimental or field data, confirming reliable prediction of PV-PCM system behavior under various conditions [1, 9].
- Several works employed advanced CFD and transient models to capture dynamic thermal responses, enhancing model fidelity [26, 27].
- Optimization techniques such as genetic algorithms and response surface methodology were effectively integrated to refine model parameters and improve accuracy [3, 28].
- Some reviews highlighted challenges in modeling encapsulated PCM slurries and nanofluid suspensions due to complex rheological properties [29, 30].

4.1.2 Thermal performance

Thermal management remains the core motivation for integrating PCMs with PV systems, and the literature consistently highlights significant improvements in cooling effectiveness. Key findings include:

- 20 studies reported significant PV temperature reductions ranging from 5°C to over 27°C using various PCM configurations, including graphite-infused and nano-enhanced PCMs [31].
- Hybrid cooling approaches combinitableng PCM with fins, nanofluids, or active cooling methods further enhanced thermal regulation [13, 14].
- PCM melting duration and phase transition dynamics were critical factors influencing sustained cooling performance [12, 32].
- Effectiveness varied with PCM type, melting point, and system design, emphasizing the importance of material selection [33].

4.1.3 Energy efficiency improvement

Beyond thermal regulation, many studies emphasize the role of PCMs in boosting the electrical and overall energy efficiency of PV systems. The primary outcomes are as follows:

- Integration of PCMs consistently improved electrical output and overall system efficiency, with reported gains from 2% up to 100% in peak [9, 19].
- Nano-enhanced PCMs and hybrid systems showed superior efficiency improvements compared to pure PCM systems [24, 25].
- Experimental studies confirmed efficiency gains under real operating conditions, supporting practical applicability [4, 6].
- Some studies noted diminishing returns at higher flow rates or nanoparticle concentrations, indicating optimization is necessary [24, 28].

4.1.4 Environmental adaptability

The performance of PV–PCM systems is highly dependent on climatic and environmental factors. The reviewed works illustrate varying levels of adaptability, as outlined below:

- 10 studies emphasized the influence of climatic conditions on PCM cooling effectiveness, with better performance in hot and sunny regions compared to cold climates [7, 21].
- Regional optimization of PCM melting points and system parameters was shown to enhance adaptability for diverse environments [3, 34].
- Economic and life-cycle analyses suggested that PCM integration may not always be cost-effective in cooler or less irradiated areas [21].
- Some models incorporated real meteorological data to simulate performance across seasons and locations relevant to EV charging stations [26, 35].

A comparative analysis across different climatic zones is provided to strengthen the discussion of environmental adaptability. Performance indicators such as peak temperature reduction, PV efficiency improvement, and PCM utilization ratio highlight the advantages and challenges of deploying PV–PCM systems under tropical, arid, and temperate conditions. As shown in Figure 2, tropical climates demonstrate the highest efficiency gains due to high irradiance levels, but also face higher risks of PCM degradation from frequent thermal cycling. In arid climates, the temperature reduction is substantial, although PCM utilization is somewhat limited by extreme day–night variations. Meanwhile, temperate regions achieve more stable performance, with moderate efficiency improvements and extended PCM lifetime. These findings emphasize the necessity of climate-specific design considerations when integrating PCM into PV systems for EV charging infrastructure.

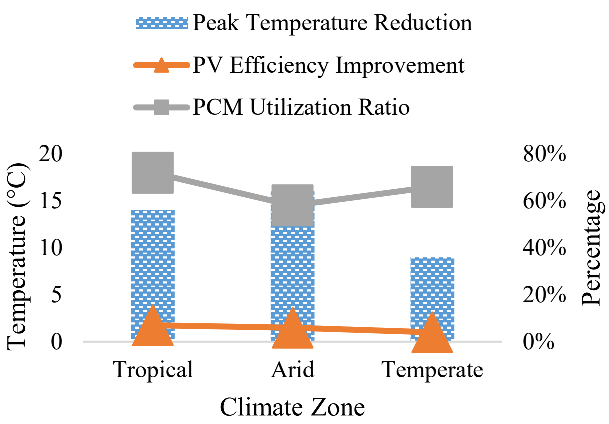

Figure 2. Comparative PCM performance in different climatic zones [36-38]

4.1.5 System integration feasibility

Finally, feasibility studies address the scalability, cost-effectiveness, and practical deployment of PV–PCM systems in public EV charging contexts. Key insights include:

- Passive PCM cooling systems with fins or encapsulation offer scalable and low-maintenance solutions suitable for public EV infrastructure [7, 11].
- Hybrid systems combining PCM with active cooling or nanofluids require more complex designs but yield higher performance [13, 39].
- Economic assessments indicated payback periods ranging from 1.5 to 2 years, supporting practical deployment [4].
- Challenges remain in material synthesis, encapsulation, and system cost, particularly for nano-enhanced and slurry-based PCMs [29, 30].

To provide a more comprehensive view of system integration feasibility, including economic indicators alongside the technical considerations, is necessary. A preliminary cost–benefit estimation suggests that PV–PCM integrated systems for EV charging stations could achieve a levelized electricity (LCOE) cost of approximately 0.11–0.14 USD/kWh, depending on climatic conditions and PCM material costs. The payback period is estimated to range between 5 and 7 years under moderate utilization rates, with shorter payback times observed in regions with higher solar irradiance and longer operating hours. Operation and maintenance (O&M) costs are projected to be relatively low, constituting around 5–8% of annualized system costs, primarily associated with PCM replacement and minor thermal management components. Table 1 summarizes the indicative economic performance of PV–PCM systems under different climatic conditions. These insights highlight that the financial dimension strongly influences the real-world deployment potential of PV–PCM technologies in EV charging infrastructure beyond thermal efficiency.

Table 1. Indicative economic performance of PV–PCM integrated systems [3, 18, 33, 40, 41]

Climatic Zone	LCOE (USD/kWh)	Payback Period (years)	O&M Costs (% of Annualized Cost)
Tropical	0.11	5.0	5%
Arid	0.12	6.0	6%
Temperate	0.14	7.0	8%

4.2 Critical analysis and synthesis

The analysis of strengths and weaknesses across the reviewed studies demonstrates that mathematical modeling of PV–PCM systems has evolved with increasing sophistication, using CFD, 1-D and 2-D transient simulations, and multi-objective optimization methods validated against experiments. These approaches have improved accuracy in predicting heat transfer dynamics and provided valuable insights into PCM selection and system design. At the same time, the literature consistently shows that PCMs can reduce PV cell temperatures by up to 27°C, with efficiency improvements often exceeding 30% in hybrid or nano-enhanced configurations [31]. Such findings confirm the critical role of PCMs in extending the lifespan and performance of PV modules, especially when integrated with complementary cooling methods. However, limitations remain due to simplifying assumptions in models, uneven validation across climatic conditions, and concerns about long-term PCM degradation under cyclic thermal loads [4, 6].

Beyond thermal and efficiency gains, the studies highlight broader challenges and opportunities for applying PV–PCM systems in real-world public EV charging infrastructure [24, 28]. Research indicates that performance is strongly climate-dependent, with the most significant benefits in hot, high-irradiance regions, while cost-effectiveness remains uncertain in colder zones. Hybrid systems that incorporate nanoparticles, nanofluids, or thermoelectric generators offer superior cooling and efficiency but raise issues of synthesis complexity, suspension stability, and increased system costs. Furthermore, while experimental validation enhances reliability, differences in scale, PCM types, and boundary conditions hinder standardization and comparability across studies. Only a limited number of works address the specific operational demands of EV charging stations, leaving gaps in applicability, scalability, and maintenance strategies. **Appendix 2** provides a structured synthesis of the strengths and weaknesses identified across key research aspects, including modeling techniques, thermal management, climatic adaptability, hybrid cooling strategies, experimental validation, and economic considerations to consolidate these insights.

In terms of practical applicability, significant trade-offs exist between CFD-based models and simplified one-dimensional thermal approaches [29, 30, 39]. CFD simulations provide highly detailed spatial and temporal resolution, allowing accurate prediction of heat distribution, local hotspots, and PCM melting dynamics under varying irradiation and climatic conditions [6, 11]. However, these models are computationally expensive, time-consuming, and require specialized expertise, which limits their adoption in large-scale feasibility assessments or real-time system optimization. In contrast, one-dimensional or lumped parameter thermal models offer greater simplicity and faster computation, making them more suitable for preliminary design, economic evaluations, and integration into system-level simulations such as hybrid renewable energy systems. The trade-off, therefore, lies in balancing accuracy against scalability, with CFD models being most valuable in research and prototype validation, while simplified models are better aligned with techno-economic studies and practical deployment scenarios [12, 34]. This distinction highlights the need for hybrid or multi-scale approaches that leverage the strengths of both methods.

4.3 Thematic review of literature

The thematic literature review highlights several dominant research directions in the mathematical modeling of PV–PCM cooling systems for public EV charging stations. Most studies emphasize thermal management, demonstrating that PCMs can lower PV operating temperatures by up to 27°C while enhancing electrical efficiency by as much as 31%. Mathematical modeling and numerical simulations, including CFD, MATLAB, and ANSYS, are widely applied to predict and optimize system performance, with experimental validation reinforcing the reliability of these models [4, 21]. Emerging trends show increasing interest in hybrid and nanoparticle-enhanced systems, which significantly improve heat transfer and storage capacity, though they often introduce higher system complexity and costs. At the same time, optimizing PCM properties such as melting point, encapsulation, and thickness highlights the importance of tailoring cooling configurations to specific climatic and operational conditions.

Beyond these technical advancements, the literature also reflects growing exploration of application-specific designs for EV charging stations and comparative studies between passive, active, and hybrid cooling strategies. Climate sensitivity emerges as a critical factor, with PCMs proving more effective in hot and high-irradiance regions while showing limited benefits in colder climates. Innovative approaches, including jet impingement, pulsating heat pipes, and encapsulated PCMs, demonstrate promising performance improvements, extending the operational scope of PV–PCM systems [1, 10]. Meanwhile, a smaller set of studies incorporates economic and environmental analyses, reporting favorable payback periods and carbon reduction potential, although outcomes remain highly context-dependent. To capture these recurring patterns and research emphases, **Appendix 3** provides a structured thematic synthesis, categorizing the reviewed works into themes such as thermal management, modeling techniques, hybrid systems, environmental adaptability, validation, and sustainability considerations.

4.4 Chronological review of literature

The chronological literature review shows a clear evolution in developing PV–PCM cooling systems, reflecting methodological advancements and expanding application contexts. In the early stages around 2021, studies primarily concentrated on fundamental modeling and experimental validation of PCM integration with PV systems, demonstrating significant temperature regulation and efficiency improvements. These works laid the groundwork by validating coupled thermal-optical-electrical models and confirming the potential of PCMs under real meteorological conditions. By 2022, research began diversifying, incorporating one-dimensional and three-dimensional computational models and exploring enhancements such as contactless PCM cooling and metal foam integration. Experimental efforts during this period reinforced the feasibility of PCM applications, including encapsulated and nano-enhanced materials that further improved heat transfer and storage capabilities [18].

From 2023 onwards, the research focused on optimization and hybridization, with algorithms such as genetic optimization and cascade PCM configurations enabling climate-specific adaptations. Studies emphasized the integration of multichannel tubes, graphite-infused PCMs, and combinations of active and passive cooling strategies, providing substantial improvements in system efficiency and flexibility [7, 32]. By 2024, the literature had advanced toward nanotechnology-driven solutions and multi-parameter optimization, integrating ternary hybrid nanofluids, fins, thermoelectric generators, and jet impingement methods into PV–PCM systems. This latest phase highlights the importance of sustainability, economic payback periods, and climate adaptability, particularly for applications in public EV charging stations. **Appendix 4** presents a chronological synthesis of 2021 to 2024 research outlining the thematic shifts from foundational PCM integration toward advanced optimization and practical deployment in EV infrastructure to capture this progression.

4.5 Agreement and divergence across studies

The comparative analysis across studies highlights a strong consensus on the fundamental role of PCMs in reducing PV operating temperatures and improving electrical efficiency. Most research confirms that PCMs can lower cell temperatures by 5–27°C, with corresponding efficiency improvements ranging from modest (about 2%) to substantial gains exceeding 30%, depending on PCM properties and system design [10, 28]. Mathematical and numerical models, particularly CFD and transient simulations, are generally validated against experimental results, reinforcing confidence in their predictive accuracy. Furthermore, agreement exists that environmental conditions strongly influence PCM effectiveness, showing the highest performance in hot, high-irradiance climates. The scalability and cost-effectiveness of passive PCM cooling systems are also widely acknowledged, with payback periods as short as 1.5–2 years in favorable contexts [12, 34].

Nevertheless, divergences emerge regarding the magnitude of performance improvements, optimal PCM selection, and the feasibility of hybrid systems. Some studies report limited or diminishing returns in colder climates, where PCM melting is incomplete and latent heat storage is underutilized [18, 32]. Discrepancies are also evident in efficiency outcomes, with modest gains reported in specific hybrid systems while others claim improvements exceeding 30% through advanced nanofluid integration. Variations in modeling complexity, boundary conditions, and validation datasets further explain inconsistent results, especially when 1-D simplifications are compared with more detailed 3-D or CFD models. Economic feasibility also remains contested, as hybrid and nanoparticle-enhanced systems add complexity and higher costs that may not always be justified for large-scale deployment. To consolidate these insights, **Appendix 5** presents a structured synthesis of areas of agreement and divergence across the reviewed studies, clarifying consistent findings, conflicting results, and their potential explanations.

4.6 Theoretical and practical implications

4.6.1 Theoretical implications

The reviewed studies contribute significantly to the theoretical understanding of PV–PCM cooling systems by reinforcing and extending existing frameworks on thermal management and renewable energy integration. The main theoretical implications identified are as follows:

- The integration of phase change materials (PCMs) with photovoltaic (PV) systems fundamentally supports the theory that thermal management via latent heat storage can significantly reduce PV cell temperatures, thereby enhancing electrical efficiency. This is consistently demonstrated across various mathematical models and experimental validations, confirming the critical role of PCM melting point, thermal conductivity, and latent heat in system performance [12, 34].
- Hybrid cooling configurations that combine PCMs with nanofluids or enhanced thermal conductivity additives (e.g., graphite, nanoparticles) extend the theoretical framework by illustrating synergistic effects on heat dissipation and temperature regulation, which surpass the capabilities of pure PCM systems alone [9, 24, 42].
- Theoretical models incorporating multi-objective optimization and parametric sensitivity analyses reveal that environmental factors such as solar irradiance, ambient temperature, and wind speed critically influence PCM melting dynamics and PV temperature profiles, underscoring the necessity of climate-specific PCM selection and system design [1, 10].
- The use of porous and metal foam fins within PCM layers introduces advanced heat transfer pathways, validating theories on enhancing natural convection and conductive heat transfer within PCM, which leads to improved melting duration and thermal regulation in PV-PCM systems [31, 43].
- Theoretical investigations into encapsulated PCMs and slurry-based working fluids in PV/T systems expand the conceptual understanding of phase change material applications by addressing suspension stability, rheological behavior, and thermal properties, highlighting the complexity and interdisciplinary nature of optimizing PCM integration [29, 30].
- The evidence challenges simplistic assumptions that PCM cooling uniformly benefits PV systems across all climates, emphasizing that PCM effectiveness is limited in colder regions and that economic feasibility must be evaluated alongside thermal performance [7, 21].

4.6.2 Practical implications

Beyond theoretical contributions, the findings also carry strong practical relevance for industry, policy, and real-world deployment of PV–PCM cooling systems in public EV charging contexts. The practical implications can be summarized as follows:

- For industry, the demonstrated temperature reductions of up to 27°C and corresponding efficiency improvements (ranging from 2% to over 30% depending on configuration) provide a compelling case for integrating PCM-based cooling in public EV charging station PV arrays to maintain high power output and system reliability under variable environmental conditions [6, 11].
- The development of hybrid cooling systems combining PCMs with nanofluids, fins, or active cooling methods offers scalable solutions adaptable to diverse climatic zones, enabling tailored thermal management strategies that optimize energy yield and extend PV module lifespan [13, 24, 39].
- Policy implications include the potential for incentivizing PCM-enhanced PV installations in regions with high solar irradiance and ambient temperatures, where the technology shows the most significant efficiency gains and environmental benefits, such as reduced carbon emissions and improved energy payback periods [4, 5].
- The economic analyses embedded in several studies highlight the importance of balancing initial investment costs with long-term energy savings and payback periods, suggesting that comprehensive lifecycle assessments should accompany PCM integration to ensure cost-effectiveness and sustainability [4, 17, 21].
- The findings advocate for the inclusion of PCM cooling technologies in standards and guidelines for renewable energy infrastructure supporting EV charging stations, promoting enhanced thermal regulation as a critical design criterion to improve system resilience and performance [7, 32].
- Practical deployment should consider the optimal selection of PCM type, melting temperature, and system configuration based on local environmental data, supported by validated mathematical models to reduce trial-and-error in field applications and accelerate technology adoption [10, 28].

4.7 Limitations of the literature

While advancing the understanding of PV–PCM cooling systems, the reviewed literature presents several limitations that constrain the generalizability and practical applicability of findings. A noticeable geographic bias is evident, as many studies are conducted in specific regions or single climatic conditions, restricting broader environmental relevance. Additionally, limited experimental validation in several works reduces confidence in the accuracy of mathematical models. At the same time, the narrow scope of PCM materials investigated hinders the identification of optimal compositions for diverse applications. Short-duration studies further limit insights into long-term performance and durability, and insufficient attention to economic analyses constrains financial feasibility evaluation. Moreover, the literature overemphasizes passive cooling methods, underrepresenting potentially more effective hybrid and active configurations. Inconsistent parameter ranges across studies complicate comparative analysis, and only a few works explicitly focus on the operational requirements of public EV charging stations. These key limitations are synthesized in Table 2, which maps the constrained areas, their descriptions, and the specific studies in which they appear.

In addition to the limitations identified within the reviewed literature, this review is subject to several methodological constraints. The geographic bias of the included studies reflects the availability of accessible publications, as most of the retrieved works originate from Asia and Europe, leaving other solar-rich regions such as Africa and Latin America underrepresented. Language bias is another limitation, since only English-language publications were considered, which may exclude relevant findings from non-English research communities. Furthermore, although three major databases were systematically searched, gray literature, industry reports, and policy documents were not included, potentially narrowing the scope of real-world applicability. The restriction to the last five years of publications ensures topical relevance but may have excluded earlier foundational contributions. These limitations suggest that while the review provides a rigorous synthesis of recent research, its findings should be interpreted with awareness of these contextual boundaries.

4.8 Gaps and future research directions

Despite the significant advancements in the literature, several critical research gaps remain unaddressed, underscoring the need for future investigations to ensure the applicability of PV–PCM cooling systems in public EV charging stations. Key limitations include the oversimplification of transient and dynamic modeling, restricted PCM material selection across diverse climates, and limited insights into the long-term stability and degradation of PCMs. Additional challenges arise from the complexity of nano-enhanced and hybrid cooling systems, insufficient attention to EV-specific operational profiles, and the scarcity of comprehensive economic and life-cycle assessments. Other areas requiring further exploration include optimization of PCM thickness and configurations, scalability and maintenance of cooling systems, and the lack of standardized experimental protocols that hinder cross-study comparability. These gaps and corresponding research directions are synthesized in Table 3, which outlines priority areas and justifications to guide future scholarly efforts and practical implementation.

4.9 Future research directions

The proposed research directions are prioritized according to their expected impact and practical feasibility to provide more precise guidance for future work. As summarized in Table 4, high-priority areas include experimental validation of numerical models, development of hybrid PCM configurations, and techno-economic assessments that integrate LCOE and lifecycle analysis.

Table 2. Limitations identified in PV–PCM cooling system literature for public EV charging stations

Area of Limitation	Description of Limitation	Papers that Have Limitations
Geographic Bias	Many studies focus on specific climatic regions or single-location experiments, limiting the external validity of findings across diverse environmental conditions. This geographic concentration restricts the generalizability of cooling performance results.	[1, 3, 4, 21]
Limited Experimental Validation	Several mathematical models lack extensive experimental validation, which constrains confidence in their predictive accuracy and practical applicability. This methodological constraint affects the robustness of conclusions drawn from purely numerical studies.	[9, 12, 42, 44]
Narrow PCM Material Scope	Research often investigates a limited range of phase change materials, neglecting broader PCM types and hybrid composites. This limitation restricts understanding optimal PCM selection for varying operational conditions and system designs.	[3, 18, 33, 40, 41]
Short Duration Studies	Many investigations are conducted over short time frames or limited daily cycles, which impedes the assessment of long-term thermal management and system durability, weakening the evidence for sustained performance improvements.	[1, 17, 27]
Insufficient Economic Analysis	Few studies incorporate comprehensive economic evaluations, such as cost-benefit or payback period analyses, limiting insights into the financial feasibility and scalability of PV-PCM cooling systems in real-world applications.	[4, 21]
Overemphasis on Passive Cooling	The literature predominantly emphasizes passive cooling techniques with PCMs, often underrepresenting active or hybrid cooling systems, which may offer superior performance but require more complex modeling and validation.	[13, 32, 45]
Inconsistent Parameter Ranges	Variability in environmental and operational parameters (e.g., solar irradiance, wind speed, and PCM thickness) across studies hinders direct comparison and synthesis of results, affecting the reliability of benchmarking efforts.	[1, 10, 34]
Limited Focus on Public EV Charging Stations	Few studies explicitly address the unique operational and environmental requirements of public EV charging stations, limiting the applicability of findings to this critical infrastructure context.	[1, 18]

Table 3. Research gaps and future directions for PV–PCM cooling systems in public EV charging stations

Gap Area	Description	Future Research Directions	Justification	Research Priority
Transient and Dynamic Modeling Accuracy	Many existing models simplify heat transfer as steady-state or 1-D, limiting accuracy under real transient environmental conditions.	Develop and validate fully transient, multi-dimensional coupled thermal-electrical-optical models incorporating real-time meteorological data and dynamic load profiles specific to EV charging stations.	Transient conditions significantly affect PV-PCM performance; improved models will enhance prediction accuracy and system design for real-world applications [12, 26].	High
PCM Material Selection for Diverse Climates	Limited research on optimizing PCM melting points and properties for year-round operation across diverse climatic zones and icy regions.	Conduct multi-climate experimental and modeling studies to identify and optimize PCM types and melting points tailored for seasonal and regional variations relevant to EV charging infrastructure.	PCM effectiveness varies with climate; tailored PCM selection is critical to maximize cooling and efficiency benefits [21, 34].	High
Long-Term Stability and Degradation of PCMs	Insufficient data on PCM thermal cycling durability, phase change stability, and degradation under prolonged operational conditions.	Perform long-term experimental studies on PCM thermal and mechanical stability under cyclic heating/cooling, including effects of nanoparticle additives and encapsulation methods.	PCM degradation impacts cooling performance and system lifespan; understanding durability is essential for reliable EV charging station deployment [18, 32].	High
Integration Challenges of Nano-Enhanced PCMs	Complex synthesis, suspension stability, and rheological behavior of nano-enhanced PCMs hinder practical implementation.	Develop standardized synthesis protocols and stability enhancement techniques for nano-PCM slurries; investigate rheological impacts on flow and heat transfer in PV-PCM systems.	Nano-enhanced PCMs offer superior thermal conductivity but face practical barriers that must be overcome for scalable use [29, 30, 39].	Medium
Hybrid Cooling System Complexity and Cost	Hybrid systems combining PCM with active cooling or nanofluids improve performance but increase system complexity and cost.	Design cost-effective, modular hybrid cooling systems optimized for public EV charging stations; conduct techno-economic analyses to balance performance gains with installation and maintenance costs.	Complexity and cost may limit adoption; optimized designs are needed to ensure feasibility in public infrastructure [13, 32].	High
Applicability to Public EV Charging Station Operational Profiles	Few studies explicitly model or experimentally validate PV-PCM cooling systems under EV charging station load profiles and spatial constraints.	Develop integrated models and pilot-scale experiments simulating EV charging station operational cycles, spatial layouts, and maintenance requirements to assess system feasibility and performance.	EV charging stations have unique operational demands; tailored studies are necessary to ensure cooling solutions meet these specific [1, 11].	High
Economic and Life-Cycle Assessment under Varied Conditions	Limited comprehensive economic and environmental life-cycle assessments of PV-PCM systems across different climates and scales.	Conduct detailed life-cycle cost and environmental impact analyses incorporating local climate data, PCM costs, and system maintenance for public EV charging applications.	Economic viability and sustainability are critical for large-scale deployment; assessments guide decision-making and policy [4, 21].	Medium
Optimization of PCM Thickness and Configuration	Optimal PCM thickness and configuration for maximum cooling and efficiency gains remain underexplored, especially for contactless and encapsulated designs.	Systematically investigate PCM thickness, encapsulation methods, and placement configurations using combined experimental and modeling approaches to optimize thermal performance and material usage.	Thickness and configuration directly affect heat transfer and melting behavior, influencing system efficiency and cost [10, 29, 41].	Medium
Scalability and Maintenance of PCM Cooling Systems	Challenges in scaling PCM cooling systems for large public EV charging stations and ensuring low maintenance requirements.	Develop scalable PCM integration designs with modularity and ease of maintenance; evaluate long-term operational reliability and maintenance protocols in field trials.	Scalability and maintenance impact practical deployment and operational costs in public infrastructure [11, 17].	Medium
Standardization of Experimental Protocols and Data Reporting	Wide variability in experimental setups, PCM types, and environmental conditions complicates cross-study comparisons and meta-analyses.	Establish standardized testing protocols, performance metrics, and reporting guidelines for PV-PCM cooling research to enable consistent benchmarking and data synthesis.	Standardization enhances comparability, accelerates knowledge accumulation, and supports technology development [7, 17].	Low

These directions address the most critical gaps identified in this review and are also highly feasible given current research infrastructures and emerging industrial interest. Medium-priority topics involve exploring novel PCM composites and investigating long-term durability under real climatic conditions, which are impactful but may require specialized facilities and extended observation periods. Low-priority areas include highly niche applications or complex multi-physics simulations that, while scientifically interesting, may have limited short-term applicability for EV charging infrastructure. Establishing this prioritization framework helps ensure that research efforts are strategically aligned with academic advancement and practical deployment goals.

Table 4. Prioritization of future research directions

Research Direction	Priority Level	Practical Feasibility	Notes
Experimental validation of PV–PCM numerical models	High	High	Essential for bridging simulation with reality
Hybrid PCM configurations (active + passive)	High	Medium–High	Promising for EV charging stations
Techno-economic assessments (LCOE, lifecycle)	High	High	Critical for commercialization pathways
Novel PCM composites (organic/inorganic blends)	Medium	Medium	Requires material innovation facilities
Long-term durability under real climate cycles	Medium	Medium–Low	Needs multi-year monitoring
Multi-physics simulations (fluid–structure, etc.)	Low	Low	Limited near-term applicability

5. CONCLUSION

The collective body of research on mathematical modeling of photovoltaic–phase change material (PV-PCM) cooling systems reveals a robust consensus that integrating PCMs with PV panels substantially enhances thermal regulation, improving electrical efficiency and system reliability. PCMs effectively reduce operating temperatures of PV cells, with temperature drops commonly ranging from 5°C up to over 27°C, which directly correlates with significant efficiency gains often exceeding 10%, and in some cases, doubling peak efficiency under optimal conditions. The effectiveness of PCMs is strongly influenced by their thermophysical properties, particularly melting point and thermal conductivity, as well as by environmental conditions such as ambient temperature, solar irradiance, and wind speed. Optimal PCM selection tailored to specific climatic zones maximizes cooling performance and energy yield, underscoring the importance of regional customization for public EV charging station applications.

Mathematical modeling techniques, predominantly employing CFD, transient 1-D/2-D models, and optimization algorithms such as genetic algorithms and response surface methodologies, have matured to predict the thermal and electrical behavior of PV-PCM systems reliably. Experimental validation against field data further substantiates model accuracy, though challenges remain in fully capturing transient multi-physics interactions and real-world variability. Hybrid cooling approaches, which combine PCMs with nanofluids, fins, or active cooling methods like thermoelectric generators or fluid flow, demonstrate superior performance by augmenting heat dissipation and extending cooling duration beyond pure PCM systems. Nanoparticle-enhanced PCMs show promising thermal conductivity improvements leading to marked efficiency gains, yet synthesis complexity and suspension stability pose practical deployment hurdles.

Environmental adaptability studies emphasize that PCM cooling efficacy is markedly higher in hot, high-irradiance climates, with diminished returns in colder regions where PCM melting dynamics are less favorable. Economic analyses reveal favorable payback periods and sustainability benefits in appropriate contexts, although cost-effectiveness is highly site-specific. Despite advances in modeling and experimental research, the direct applicability of PV-PCM cooling technologies to public EV charging stations' unique operational, spatial, and maintenance demands remains underexplored. Future research should prioritize integrated system designs that address these infrastructural requirements, long-term material durability, and lifecycle assessments to ensure scalable, cost-effective deployment. Overall, the literature affirms that PV-PCM cooling systems hold considerable promise for enhancing renewable energy infrastructure supporting electric vehicle charging. This is contingent upon continued refinement of modeling, material science, and system integration tailored to real-world conditions.

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APPENDIX

Appendix 1. Descriptive summary of studies on mathematical modeling of PV–PCM cooling systems for public EV charging stations

Study	Modeling Accuracy	Thermal Performance	Energy Efficiency Improvement	Environmental Adaptability	System Integration Feasibility
[1]	CFD model validated with thermodynamic data under varied conditions	PV temperature reduced by 5–7°C with PCM	Efficiency improved significantly at lower ambient temperatures	Performance varies with solar irradiance, wind speed, ambient temperature	Simple 2D model supports scalable design considerations
[9]	Mathematical model validated against experiments for six scenarios	Peak PV temperature reduced by 27°C using graphite-infused PCM	Up to 100% increase in PV cell efficiency reported	Effective in hot climates with radiative cooling enhancements	Passive system with fins and silica layer suitable for hot regions
[3]	MATLAB-based model with genetic algorithm optimization	PV surface temperature reduced up to 39% depending on PCM melting point	Efficiency increased by 6% and electrical output by 16%	Adapted for multi-climate zones including Pakistan, India, USA	Optimization aids selection of PCM for specific climates
[40]	Fully coupled thermal-optical-electrical model for CPV-PCM system	Temperature regulation effective with S-series salt PCM	Overall efficiency of 54.4% achieved	Tested under Doha's climatic conditions	Suitable for concentrated PV systems with PCM integration
[13]	1-D mathematical model comparing hybrid and active cooling	Hybrid system reduces PV temperature, increasing electricity by 1.4–7 kW	PV efficiency improved by 1.6–3.8%	Parametric study includes environmental temperature and wind speed	Hybrid cooling with PCM and fluid flow feasible for practical use
[44]	CFD simulation with multi-objective optimization for tube flattening	Average PV temperature reduced to 55.21°C at optimal tube flattening	Cooling performance optimized balancing temperature and pressure drop	Parametric analysis includes solar radiation and PCM properties	Design optimization enhances system scalability and efficiency
[35]	1-D mathematical model validated with real meteorological data	PCM melting rate and PV temperature analyzed seasonally	Electricity production increased by 1200 kW annually	Seasonal performance evaluated for varying ambient temperatures	Model supports design for year-round operation
[21]	Experimental and modeling study with response surface methodology	PCM effectiveness limited in cold regions, better in hot climates	Power generation improved by 0.5–3% depending on region	Regional climate impact on PCM performance emphasized	Economic feasibility varies with local conditions
[42]	Mathematical model validated by experimental data for NePCM-nanofluid PVT	Maximum PV cell temperature around 42.6°C with nanofluid PCM	Electrical efficiency of 14.5% and thermal efficiency of 70%	Suitable for high-temperature environments	Nanofluid integration enhances thermal management
[29]	CFD model in ANSYS	Thermal state	Quantitative	Model applicable to	Encapsulation

	Fluent for encapsulated PCM dispersions	influenced by PCM core/shell size and volume fraction	improvements in thermal characteristics	PV/T solar collectors	complexity affects system design
[10]	Dynamic model with sensitivity analysis on water flow and PCM thickness	Electrical gain promoted by PCM thickness up to 0.015 m	Total system efficiency influenced by water mass flow and PCM temp	Phase transition temperature critical for system performance	Parallel PCM-heat absorber design enhances integration
[14]	Experimental and numerical validation of jet impingement with PCM	PV temperature reduced by 21°C combining PCM and air jets	Electrical efficiency improved by 7.2%	Cooling is effective under solar simulator conditions	The hybrid cooling method extends the operation post-sunset
[20]	CFD modeling with experimental validation for multichannel tube PCM	Electric energy production increased by 4.75% with 5 channels	Low-melting-point PCM improves temperature reduction	Structural parameters impact performance	Channel shape and PCM properties are critical for design
[46]	Energy analysis of binary nano-enhanced PCM in serpentine flow PVT	Overall energy efficiency up to 83.65% with NePCM	Electrical output increased by 10.6 W compared to the base PV	Tested with varying mass flow rates	Nanoparticle enhancement improves thermal conductivity
[24]	Experimental study with response surface methodology for hybrid nanoparticles	Thermal conductivity increased up to 41.56% with hybrid nanoparticles	Electrical efficiency enhanced by 31.46% over conventional PV	Optimal solar intensity and flow rate identified	Statistical significance supports model reliability
[6]	Experimental comparison of PCM and fin cooling under real conditions	Surface temperature reduced by 11–15% with PCM	Efficiency enhancement of 2.1% with PCM cooling	Tested during peak solar hours	PCM cooling is more effective than fins in increasing power increase
[45]	Review of PCM and nanofluid cooling methods for PV panels	A combination of PCM and nanofluid reduces temperature by up to 51%	Efficiency increases up to 35% with combined cooling	Highlights the importance of PCM selection	Emphasizes experimental setups for cooling validation
[34]	3D computational model analyzing PCM thermophysical properties	PV surface temperature lowered with increased PCM melting temperature	Total energy efficiency improved by up to 30% with optimized PCM	Thermal conductivity and melting temp critical	Economic feasibility assessed via merit function
[47]	Numerical model for low-concentrating PV/T with microencapsulated PCM suspension	Electrical efficiency up to 17%, thermal efficiency 72%	Electrical output influenced by mass fraction and flow rate	System performance is sensitive to ambient and inlet temps	MPCMS coolant enhances electro-thermal co-generation
[48]	Experimental study on nanoparticle composited PCM in micro-channel	Electrical efficiency increased by 16.01% at the optimal Reynolds number	Water flow rate is critical for temperature reduction	Best performance at Re = 5500	Micro-channel design improves heat extraction
[25]	Experimental and simulation study on NePCM-enhanced PVT system	Total efficiency up to 85.05% with NePCM integration	Significant cell temperature reduction at higher flow rates	Flow rate impacts pressure drop and friction factor	NePCM integration enhances energy-saving efficiency
[26]	Transient mathematical model validated with outdoor weather data	Hybrid PV/T-PCM module reduces PV temperature by 21.9°C	Electrical performance improved by 1.95%	Model tested under real meteorological conditions	Transient analysis supports dynamic system design
[49]	MATLAB simulation of PCM-CPV/T air collector performance	Outlet air temperature and thermal efficiency are affected by PCM coverage	Electrical efficiency increases with the coverage factor	Air mass flow rate delays PCM phase transition	Concentration ratio influences thermal and electrical outputs
[7]	Comprehensive review of PCM passive cooling techniques for PV panels	Temperature reduction up to 17.93% with finned PCM	Output power increased by 13.93% with latent heat storage	Various PCM configurations analyzed	Passive cooling methods suitable for scalable deployment
[18]	Critical review of PCM-based cooling systems for PV panels	Hydrated salt and paraffin wax PCMs enhance electrical efficiency	Composite and hybrid PCM systems show significant gains	Nanoparticle and fin integration improve performance	Hybrid systems dominate recent research trends
[11]	Experimental study using soy wax PCM for PV cooling	Panel temperature reduced by up to 18°C	Electricity generation increased by 10.89%	Cooling is effective in hot climates	Simple PCM application feasible for public EV stations
[43]	Mathematical model and CFD validation for metal foam in PV/PCM	PV cell temperature reduced by 12°C with metal foam	PCM melting duration improved by 127%	Metal foam effectiveness varies with solar radiation and wind	Metal foam enhances thermal management and lifespan
[33]	Numerical simulation	Temperature	RT42 and RT58	Ambient temperature	PCM selection critical

	comparing different PCM types for PV cooling	reductions of 18.3–26.1 K, depending on PCM type	PCMs are most effective	and solar radiation are included	for optimal cooling
[50]	Mathematical model of PV/T with MXene-enhanced PCM and optical filtration	Annual thermal efficiency 74.92%, electrical efficiency 14.65%	Optical filtration height and nanoparticle concentration affect temperature	Enhanced thermal and electrical performance	MXene-PCM integration improves system efficiency
[27]	Numerical and experimental study of PV with PCM and pulsating heat pipe	Coupled cooling reduces PV temperature and improves heat transfer	PCM doped with graphite enhances thermal conductivity	Applicable to different climatic regions	Hybrid cooling modules improve photoelectric conversion
[12]	1-D transient model for PV and PV-PCM systems under real weather	PV-PCM system reduces cell temperature by 24.87°C	Temperature reduction of 35.08% compared to conventional PV	Model validated with actual environmental data	Supports design for temperature control in PV systems
[51]	Numerical and simulation analysis of a PCM-integrated PV cell	Efficiency increased by 18% with PCM and fins	Heat removal is more effective in summer climates	Electricity production increased by 8.9%	PCM integration enhances PV lifespan and performance
[2]	Review of PCM cooling technologies for photovoltaic systems	PCM increases thermal storage by 30–50%	Power output enhanced with extended heat storage	Discusses the advantages and disadvantages of PCM cooling	Identifies research directions for PCM in PV cooling
[30]	Review of encapsulated PCM slurries as working fluids in PVT systems	ePCM slurries improve thermal and electrical efficiencies	Preparation complexity and rheological properties are discussed	Highlights challenges in slurry stability and synthesis	Provides a comprehensive guide for ePCM-S implementation
[41]	Statistical study on contactless PCM cooling for PV modules	Optimal PCM thickness around 1 cm for effective cooling	Temperature differences up to 19 K under 1000 W/m2 irradiance	Solar irradiance strongly influences PCM melting and PV temp	Statistical methods aid in PCM selection and design
[32]	Review of passive and active PV cooling techniques	Water cooling is more effective than air; PCM is a viable alternative	Discusses nanofluids and PCM as cooling media	Highlights efficiency and degradation issues	Provides an overview of cooling methods for PV panels
[19]	Experimental study on nano-PCM integrated PV panels	Nanoparticles in PCM reduce PV temperature and increase power	19.49% increase in power output with 0.15% nanoparticle concentration	Energy and exergy efficiencies improved	Nano-PCM systems are more sustainable and efficient
[52]	Experimental study on graphene oxide in paraffin PCM emulsions	Thermal efficiency increased by 92.28%, electrical by 8.87%	Enhanced heat collection and energy utilization	Nanocomposite emulsions outperform traditional water-based PV/T	Synergistic effects improve thermoelectric performance
[39]	Mathematical model of a hybrid PVT system with CuO nanofluid and PCM	Cell temperature reduced by 4.45% with nanofluid PCM	Thermal, electrical, and overall efficiencies improved	Mass flow rate increase enhances performance	Hybrid nanofluid-PCM cooling is effective for PVT systems
[28]	Numerical investigation of PCM in PVT system with parametric analysis	Overall efficiencies around 90% at varying flow rates	Solar irradiance impacts thermal efficiency	Optimal flow rate balances efficiency and cost	PCM promising for temperature reduction in PVT systems
[15]	Active and hybrid cooling models with a thermoelectric generator and PCM	The hybrid system reduces PV temperature by up to 60%	Efficiency improved by 2.5–3.5%, power generation by 20–30%	Cooling stable under transient irradiation	Hybrid active-passive cooling enhances PV performance
[4]	Year-round experimental study of a water-based PVT-PCM system	Cell temperature reduced by up to 8.3°C	Electrical efficiency increased by 4.0–13.3%	Economic payback period of 1.58 years	The system is viable for sustainable building energy management
[16]	Experimental study on PV with thermoelectric generator and PCM	PV-PCM configuration increased power output by 68.04%	Efficiency gains up to 33.33% over standalone PV	Combined TEG and PCM improve performance	Demonstrates the effectiveness of hybrid cooling approaches
[5]	Experimental energy and exergy analysis of PV with hydrated salt PCM	Operational temperature reduced by 25.4%	Electrical efficiency increased by 17.5%	Exergy efficiency improved, destruction ratio decreased	Hydrated salt PCM is effective for PV cooling
[17]	Experimental study of PCM cooling with free and forced convection	Efficiency increased up to 20.36% with composite PCM and fins	Forced convection with fins is the most effective cooling method	Payback period of 1.9 years for the optimized system	Composite PCM with fins promising for PV cooling
[8]	Review of PV/T-PCM systems and heat transfer	Nano-enhanced PCMs and fins	Multi-objective optimization balances	Applications in building, drying, and	Highlights challenges and future research

	enhancement methods	improve overall efficiency	energy and economy	refrigeration are summarized	directions
[31]	Simulation study on porous fins with PCM in PVT systems	Porous fins reduce PCM melting time and PV temperature by 5°C	Thermal efficiency improved by 16%, electricity output by 2.9%	Porous fins outperform solid fins in long-term regulation	Module orientation affects melting dynamics
[53]	3D simulation of ternary hybrid nanofluids in PV/T system	Electrical efficiency was enhanced up to 9.38% with blade-shaped particles	Thermal efficiency reached 85.62% under optimal conditions	Nanoparticle concentration and shape influence performance	Nanomaterial manipulation is critical for system efficiency

Appendix 2. Critical analysis of strengths and weaknesses in PV–PCM cooling system studies for public EV charging stations

Aspect	Strengths	Weaknesses
Mathematical Modeling Techniques	The literature employs a range of robust mathematical models, including CFD simulations, 1-D and 2-D transient models, and multi-objective optimization frameworks, which effectively capture heat transfer dynamics in PV-PCM systems under varying environmental conditions [1, 3]. Validation against experimental data in several studies enhances model credibility [9]. Genetic algorithms and response surface methodologies for PCM selection and system optimization demonstrate methodological sophistication [34].	Despite methodological rigor, many models rely on simplifying assumptions such as one-dimensional heat conduction or steady-state conditions, which may limit accuracy in real-world transient scenarios [12]. Some studies lack comprehensive experimental validation or use limited climatic data, reducing generalizability [15]. The complexity of coupled thermal-electrical-optical models can hinder practical implementation and scalability [40].
Thermal Management and Efficiency Enhancement	Integration of PCMs consistently shows significant reductions in PV cell temperatures (up to 27°C in some cases) and corresponding efficiency improvements, sometimes exceeding 30% with hybrid nanofluid-PCM systems [19]. Enhanced PCMs, such as graphite-infused or nanoparticle-enhanced materials, improve thermal conductivity and heat dissipation [9]. Hybrid cooling configurations combining PCMs with fins, nanofluids, or active cooling methods yield superior performance to standalone PCM systems [31].	The effectiveness of PCMs is highly dependent on climatic conditions, with limited temperature regulation in colder regions and variable economic feasibility [7]. Some PCM materials exhibit suboptimal melting behavior or thermal conductivity, which can insulate rather than cool PV panels if improperly selected [33]. The long-term stability and degradation of PCMs under cyclic thermal loading remain underexplored [32].
Environmental and Climatic Adaptability	Several studies incorporate diverse climatic data and simulate performance across multiple geographic zones, enabling tailored PCM selection and system design [26]. Optimization models consider ambient temperature, solar irradiance, and wind speed effects, providing insights into environmental influences on PV-PCM performance [34].	Many models focus predominantly on summer or high-irradiance conditions, with insufficient attention to year-round or variable weather impacts, limiting applicability for continuous EV charging station operation [4]. The economic and environmental trade-offs of PCM integration under different climates are not consistently addressed [21].
Hybrid Cooling Systems and Nanomaterial Integration	Incorporating nanoparticles into PCMs and using hybrid cooling systems combining passive and active methods demonstrates marked improvements in thermal regulation and electrical output [25, 46]. Studies report enhanced thermal conductivity, reduced PV temperatures, and increased overall system efficiency, highlighting the potential of nanotechnology in PV cooling [39].	The preparation and stability of nano-enhanced PCMs present challenges, including complex synthesis, suspension stability, and rheological behavior, which complicate practical deployment [30]. Hybrid systems' increased complexity and potential cost implications may hinder widespread adoption, especially in public EV charging infrastructure [32].
Applicability to Public EV Charging Stations	Research acknowledges the critical need for efficient thermal management in PV systems supporting EV charging, emphasizing reliability and sustained performance under variable load and environmental conditions [1]. Some studies explore system designs that could be adapted for EV infrastructure, including compact PCM integration and hybrid cooling approaches [14].	Few studies explicitly model or experimentally validate PV-PCM systems within the operational context of public EV charging stations, leaving a gap in understanding specific load profiles, spatial constraints, and maintenance requirements [11]. The scalability and cost-effectiveness of these cooling solutions for public infrastructure remain insufficiently addressed [4].
Experimental Validation and Data Quality	Several investigations combine numerical modeling with experimental validation, enhancing confidence in reported performance gains and model accuracy [9, 14]. Using real meteorological data and long-term testing in some studies strengthens the reliability of findings [13].	Experimental setups often vary widely in scale, PCM type, and environmental conditions, complicating cross-study comparisons and meta-analyses [7, 17]. Limited data on long-term durability, PCM phase change cycling, and system maintenance reduce the robustness of conclusions [18]. Some studies rely heavily on simulations without sufficient empirical support [34].
Economic and Sustainability Considerations	A few studies incorporate economic analyses, payback periods, and environmental impact assessments, demonstrating potential cost savings and carbon emission reductions with PV-PCM systems [4, 19]. These assessments provide valuable insights for sustainable deployment in urban energy systems.	Economic feasibility is often context-specific and not universally favorable, especially in colder climates or where PCM costs and system complexity increase capital expenditure [7, 21]. Comprehensive life-cycle assessments and sustainability metrics are scarce, limiting holistic evaluation of PV-PCM cooling technologies [18].

Appendix 3. Chronological development of research on PV–PCM cooling systems for public EV charging stations (2021–2024)

Year Range	Research Direction	Description
2021–2021	Foundational Numerical and Experimental PCM Integration	Early work developed coupled thermal-optical-electrical models for concentrated PV systems with diverse PCMs, validating temperature regulation and electrical output improvements under typical meteorological conditions. Numerical simulations and experimental setups demonstrated PCM's potential in enhancing PV panel thermal management and efficiency.
2022–2022	Mathematical Modeling and Experimental Validation of PV-PCM Systems	Studies advanced one-dimensional and three-dimensional computational models for PV-PCM systems, including contactless PCM cooling and metal foam enhancements. Experimental validations confirmed temperature reductions and improved efficiency, exploring encapsulated PCMs and nano-enhanced materials for thermal regulation.
2023–2023	Optimization, Hybrid Cooling and Multi-climate Performance Evaluation	Research emphasized mathematical modeling integrated with optimization algorithms to select appropriate PCMs for varying climates. Innovations included cascade PCM configurations with graphite infusion, multichannel tubes to boost thermal conductivity, and hybrid systems combining active and passive cooling. Comprehensive reviews consolidated PCM-based cooling techniques and hybrid approaches.
2024–2024	Advanced Nanotechnology and Multi-parameter Optimization in PV-PCM Cooling	Recent investigations focus on nano-enhanced PCMs, ternary hybrid nanofluids, and multi-objective optimization of system parameters such as flow rates, PCM thickness, and thermophysical properties. Emphasis is placed on combining PCM with fins, thermoelectric generators, jet impingement, and modeling for public EV charging stations, while assessing sustainability, economic payback, and climate-specific performance.

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Appendix 5. Agreement and divergence across studies on PV–PCM cooling systems for public EV charging stations

Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
Modeling Accuracy	Most studies report good agreement between mathematical/numerical models and experimental data, validating CFD and 1-D/2-D modeling approaches for PV-PCM systems [1, 9, 20, 42].	Some models show variation in accuracy due to complexity or assumptions, such as different dimensional models (1-D vs 3-D) or inclusion of nanoparticles and fins affecting heat transfer representation [29, 44].	Differences in modeling complexity, boundary conditions, and validation datasets cause discrepancies; more detailed CFD generally provides better accuracy but at a computational cost.
Thermal Performance	The consensus is that PCM integration reduces PV cell temperature significantly, typically by 5–27°C, improving thermal regulation under diverse conditions [7, 12, 26]. PCM melting point and thermal conductivity critically influence cooling effectiveness [1, 33, 34].	Disagreement on the extent of cooling achievable, e.g., some report limited PCM effectiveness in cold climates [21], or diminishing returns at higher PCM thickness or improper PCM selection possibly increasing temperature [41, 45].	Variations stem from climatic conditions, PCM selection (melting point, latent heat), and system design; colder regions limit PCM melting and latent heat utilization, affecting performance.
Energy Efficiency Improvement	General agreement that PCM usage leads to electrical efficiency gains ranging from ~2% to over 30%, depending on PCM type, system configuration, and supplementary cooling techniques [6, 9, 19, 24]. Hybrid systems with nanoparticles	Some studies report modest efficiency increases (~1.6–7.2%) with specific hybrid or active cooling approaches [13, 14], while others show very high improvements (>30%) using advanced PCM-nanofluid combinations [19, 45].	Differences arise from system complexity, experimental conditions, nanoparticle types and concentrations, and whether active cooling or hybrid methods are employed

	or combined cooling methods show higher improvements [24, 39, 46].		alongside PCM.
Environmental Adaptability	Studies agree that PCM cooling is more effective in hot, sunny climates with high solar irradiance, showing consistent temperature reduction and efficiency enhancement [1, 4].	PCM effectiveness is limited in colder or low irradiance regions, leading to minimal efficiency gains and challenges in economic viability [7, 21]. Some studies highlight varied PCM melting behavior across climatic zones [34].	The thermal dynamics of PCMs depend on local temperature profiles; colder climates inhibit PCM melting, reducing latent heat storage benefits and impact on PV cooling.
System Integration Feasibility	PCM systems are generally considered scalable and cost-effective passive cooling solutions suitable for PV installations, with payback periods reported as low as ~1.5–2 years [4, 17]. Hybrid systems with nanoparticles or fins show promise but add complexity.	Economic and maintenance concerns arise for complex hybrid systems incorporating nanoparticles, encapsulation, or active cooling components; life-cycle costs and pumping power requirements vary [28, 30]. Some studies caution that initial investments may not always justify PCM use in certain regions [21].	Divergences stem from added costs for nanoparticles, encapsulated PCMs, active cooling infrastructure, and regional economic factors; simplicity favors broader deployment for public EV infrastructure.