

Systematic review of battery cooling technologies in electric vehicles: Methods, challenges, and recent innovations

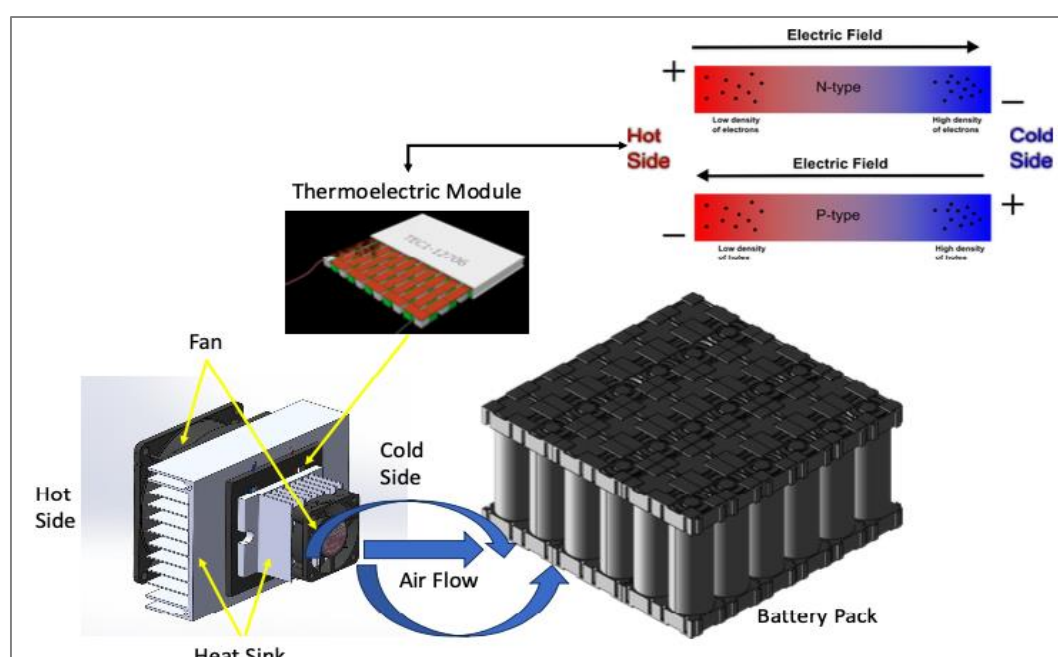
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Highlights:

- Thermal management is crucial for enhancing performance and longevity.
- liquid cooling systems offer superior efficiency but involve complex designs and higher costs.
- A multidisciplinary approach has emerged, integrating materials engineering, heat transfer, and systems design.

Abstract

This study presents a comprehensive review of battery cooling technologies in electric vehicles (EVs), focusing on their effectiveness, challenges, and recent innovations. The research methodology involved analyzing various cooling methods, including air cooling, liquid cooling, phase change materials (PCM), and thermoelectric cooling systems, through a systematic literature review. The study evaluated these technologies based on their thermal efficiency, design complexity, implementation costs, and performance across different environmental conditions. The findings reveal that while air cooling offers simplicity and cost-effectiveness, it demonstrates limited thermal efficiency for high-performance applications. Liquid cooling systems, despite higher complexity and costs, provide superior thermal management, maintaining battery temperatures within optimal ranges. PCM-based systems effectively manage short-term heat spikes but face limitations in thermal conductivity and long-term stability. Hybrid cooling solutions, particularly those combining PCM with liquid cooling, showed significant improvements in thermal

efficiency, achieving temperature reductions of 40-50 °C compared to conventional methods. The integration of nanotechnology, specifically through nanofluids and graphene-based materials, enhanced heat transfer efficiency by 20-30%. The study concludes that future developments in EV battery cooling systems will increasingly integrate artificial intelligence and smart technologies for adaptive thermal management, while hybrid cooling solutions emerge as the most promising approach for optimizing battery performance and longevity. These advancements are crucial for the continued evolution of electric vehicle technology and sustainable transportation solutions.

Keywords: Battery thermal management systems; Liquid cooling; Phase change materials; Thermoelectric cooling; Hybrid cooling systems; Thermal efficiency

1. Introduction

Electric vehicles (EVs) are increasingly recognized for their potential to mitigate greenhouse gas emissions, primarily through the use of lithium-ion batteries (LIBs) that require effective thermal management to ensure optimal performance and safety. The battery cooling system is essential in regulating the temperature of LIBs, as excessive heat can lead to diminished capacity, reduced lifespan, and safety hazards such as thermal runaway [1], [2], [3]. Various cooling techniques have been developed, including air cooling, liquid cooling, and advanced methods like heat pipes and phase change materials, each with distinct advantages and limitations [4], [5], [6]. Recent studies emphasize the importance of coolant selection and system design, with findings indicating that a 50% ethylene glycol-water solution significantly enhances cooling efficiency compared to pure water [2]. Moreover, the integration of innovative technologies, such as nanofluids in heat pipes, further improves thermal management, thereby supporting the reliability and longevity of EV batteries [6]. Continued research in this area is crucial for advancing EV technology and promoting sustainable transportation solutions [7].

In modern battery technology, effective thermal management is crucial for enhancing performance and longevity, particularly in lithium-ion batteries used in electric vehicles [8]. Air cooling, while simple and cost-effective, suffers from limited heat transfer capacity, making it suitable primarily for low-capacity applications [9], [10]. Conversely, liquid cooling systems offer superior efficiency but involve complex designs and higher costs [9]. Recent innovations, such as Phase Change Materials (PCM), have shown significant promise; for instance, PCM can reduce battery temperatures by 40-50 °C, effectively acting as a heat sink [11]. Additionally, hybrid systems combining PCM with nanofluids and fins have demonstrated improved cooling performance, with reductions in battery temperature by over 11 °C compared to conventional methods [12], [13]. The integration of advanced materials like graphene and the development of hybrid cooling systems are paving the way for more efficient thermal management solutions, essential for the future of electric vehicle technology [13], [14].

Recent advancements in thermal management for electric vehicles (EVs) highlight innovative solutions that address the challenges of optimizing thermal efficiency while considering cost, weight, and space constraints. A multidisciplinary approach has emerged, integrating materials engineering, heat transfer, and systems design. For instance, an integrated cooling system proposed by Anandan *et al.* reduces component count by 30%, enhancing efficiency and saving space [15]. Additionally, El Afia *et al.* advocate for immersion cooling as a superior method for battery thermal management, outperforming traditional indirect liquid cooling in temperature control [16]. Murphy and Akrami's comparative study of cooling designs demonstrates that optimized liquid cooling can significantly improve temperature regulation, albeit with potential weight trade-offs [17]. Furthermore, Trivedi emphasizes the importance of coolant selection and channel design in indirect cooling systems, revealing that a 50% ethylene glycol-water solution enhances performance [2]. Lastly, Mahmood *et al.* utilize advanced modeling techniques to optimize thermal management, achieving notable reductions in maximum temperature and pressure drop [18]. Collectively, these studies underscore the ongoing efforts to enhance thermal efficiency in EVs while promoting environmental sustainability.

This article aims to provide a systematic review of battery cooling technologies in electric vehicles, focusing on existing methods, challenges in implementation, and recent innovations under development. By combining literature review and analysis of current technologies, this article aims to provide a comprehensive insight into the future direction of battery cooling system development. The scope of the research includes the evaluation of various cooling methods, ranging from conventional ones such as air and liquid cooling, to innovative approaches based on nanotechnology and advanced materials. In addition, the challenges faced in each method as well

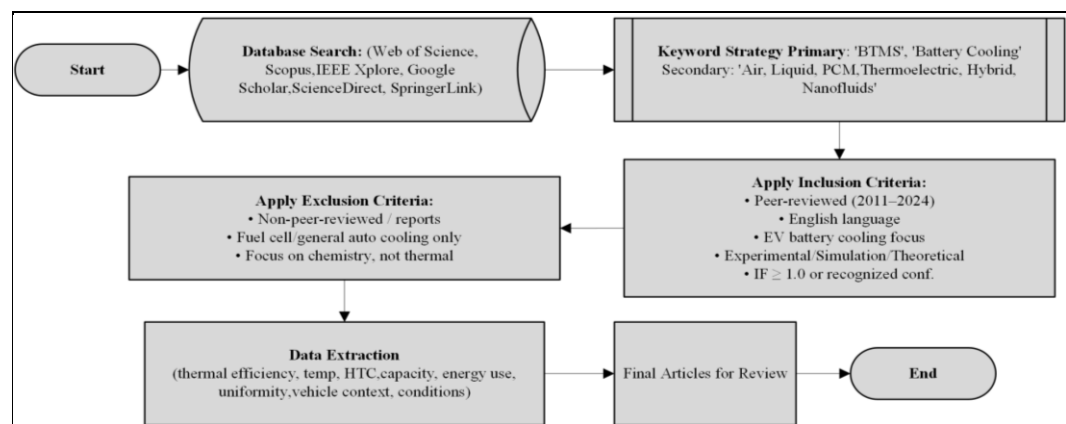
as opportunities for further improvement are discussed. This review is expected to serve as a guide for researchers and practitioners in developing efficient, safe and sustainable battery cooling solutions for electric vehicles.

Despite the growing body of research on battery cooling technologies, there remains a critical need for a comprehensive review that synthesizes current knowledge, identifies research gaps, and provides direction for future developments. This review is particularly timely given the rapid advancement of EV technology and the increasing demands for more efficient, safer, and more sustainable cooling solutions. By systematically analyzing various cooling methods, their advantages, limitations, and recent innovations, this review aims to facilitate informed decision-making in both research and practical applications, ultimately contributing to the broader goal of accelerating the transition to sustainable transportation through improved EV battery technology.

2. Methodology

This systematic literature review examined battery cooling technologies in electric vehicles by following established engineering review guidelines. A comprehensive search was conducted across six major databases, namely Web of Science, Scopus, IEEE Xplore, Google Scholar, ScienceDirect, and SpringerLink. The search strategy was developed using a combination of primary keywords such as “battery thermal management,” “battery cooling,” “electric vehicle cooling,” and “BTMS”, together with secondary terms including “air cooling,” “liquid cooling,” “PCM cooling,” “thermoelectric cooling,” “hybrid cooling,” and “nanofluids.” Boolean operators were applied to refine and expand the search results. The research flow diagram is shown in [Figure 1](#).

Figure 1.
Methodology for the
selection and
acquisition of
relevant papers in
this study



To ensure quality and relevance, specific inclusion and exclusion criteria were adopted. The review included peer-reviewed journal articles and conference proceedings published between 2011 and 2024, written in English, and focused on EV battery cooling technologies. Only studies presenting experimental data, simulation results, or theoretical analyses were considered, and publications were further restricted to those appearing in journals with an impact factor of at least 1.0 or in recognized conferences. Excluded from the review were non-peer-reviewed articles, commercial reports, studies limited to fuel cell or general automotive cooling, and research primarily addressing battery chemistry rather than thermal management.

Data extraction was conducted systematically, covering technical parameters such as thermal efficiency, operating temperature, and heat transfer coefficients; performance metrics including cooling capacity, energy consumption, and temperature uniformity; and application contexts such as vehicle configuration, environmental conditions, and integration complexity. The analysis process involved comparative evaluation, performance benchmarking, identification of emerging trends, and assessment of research gaps.

Despite its comprehensive scope, this review was subject to certain limitations. Restricting the analysis to English-language publications may have introduced a geographic bias. Furthermore, differences in experimental conditions, measurement standards, and cost-reporting methodologies across the reviewed studies could affect comparability. Finally, the availability of long-term performance data remains limited within the current body of literature.

2.1. Main Cooling Methods

2.1.1. Air cooling

Air cooling is a widely adopted thermal management technique for lithium-ion batteries in electric vehicles, primarily due to its simplicity, low cost, and ease of implementation. This method utilizes ambient air to absorb heat generated during battery operation, effectively maintaining optimal temperature ranges crucial for battery performance and longevity [19], [20]. Research indicates that air cooling systems are particularly beneficial in smaller and hybrid electric vehicles, where space and weight constraints are significant considerations. Figure 2 is a diagram of battery cooling using air [5], [21]. However, while air cooling is economical, it may not provide the same efficiency as liquid cooling systems, which offer higher heat transfer coefficients and better temperature uniformity [20]. The ongoing exploration of hybrid cooling systems, which combine air cooling with other methods like phase change materials, aims to enhance thermal management further, addressing the limitations of conventional air cooling [21], [22].

The efficiency of air cooling systems for lithium-ion batteries is significantly influenced by ambient temperature and airflow capacity, particularly under high-temperature conditions where performance declines, leading to potential overheating. This challenge is exacerbated in large-capacity batteries due to high heat density, necessitating advanced thermal management solutions. Recent developments include optimized air duct designs and adaptive airflow control through integrated sensors, which enhance cooling performance by adjusting to thermal requirements [9], [23]. Studies have shown that innovative configurations, such as variable vent positions and flow-diverting arrangements, can improve heat transfer and reduce temperature disparities, thereby enhancing battery safety and longevity [24]. While air cooling remains a cost-effective option, its limitations in high-demand scenarios highlight the need for hybrid systems or alternative methods like liquid cooling, which, despite being more complex, offer superior thermal management capabilities [25]. Air cooling is a simple and cost-efficient technique, although it has limited cooling capacity and is less effective at high power levels.

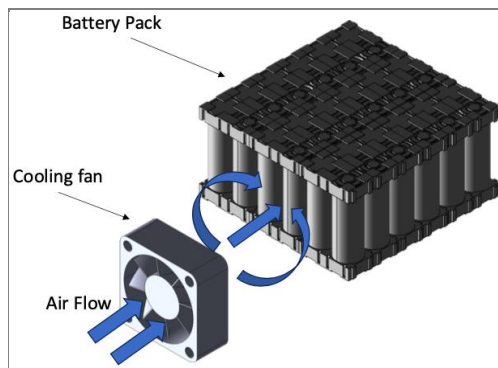


Figure 2.
Battery air
conditioning system

2.1.2. Liquid cooling

Liquid cooling systems are increasingly recognized for their superior efficiency in managing the thermal demands of high-performance electric vehicle (EV) batteries, particularly those with high power densities. These systems utilize coolants, such as water-glycol mixtures, which possess a higher specific heat capacity than air, facilitating more effective heat transfer. While liquid cooling consistently outperforms air cooling in terms of ΔT reduction from 48.7 °C to 30.7 °C [26], this improvement comes at the expense of system complexity and leakage risks, which limit scalability for mass-market low-cost EVs. Furthermore, most reported studies are based on laboratory-scale modules with controlled coolant flow, very few validate long-term performance under real-world driving cycles or tropical climates, representing a critical research gap. Additionally, innovative designs, such as those employing serpentine flow channels and optimized

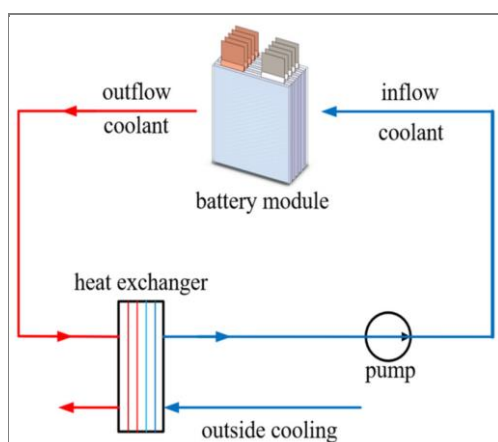


Figure 3.
Liquid cooling
system with
components [31]

cooling plate materials, have demonstrated improved thermal management performance and energy efficiency [27], [28]. The implementation of advanced control strategies, like sliding mode control, further enhances the responsiveness of these systems to real-time thermal changes, ensuring optimal operating conditions [29]. Overall, liquid cooling emerges as a critical technology for advancing battery thermal management in modern EVs [30]. The water-based battery cooling workflow is shown in Figure 3.

The implementation of liquid cooling systems for electric vehicle batteries presents

significant challenges, primarily due to the complexity and additional components required, such as pumps and heat exchangers, which increase both cost and weight [2], [32]. Moreover, the risk of fluid leakage poses a potential threat to battery safety [32]. To address these issues, recent innovations focus on utilizing nanofluids and advanced materials that enhance thermal efficiency while minimizing space and weight requirements [31], [32]. For instance, studies have shown that nanofluid mixtures, such as Al_2O_3 in water, can significantly improve heat transfer rates, while the integration of phase change materials (PCMs) with metal foams can optimize temperature control during battery operation [32], [33]. These advancements not only mitigate the risks associated with traditional cooling methods but also enhance the overall performance and longevity of battery systems [29]. The liquid cooling has high thermal conductivity and effective for high-power batteries, but more complex and costly and risk of leakage.

2.1.3. Phase Change Materials (PCM) cooling

PCM-based cooling systems are increasingly recognized for their effectiveness in managing thermal conditions in lithium-ion batteries, particularly in high-demand applications like electric vehicles. These systems utilize materials that undergo phase changes, such as paraffin wax, to absorb latent heat during battery operation, significantly reducing peak temperatures from potentially hazardous levels. The working principle of PCM is illustrated in Figure 4 [11]. The integration of PCMs allows for passive thermal management, enhancing energy efficiency without additional energy input [7]. Recent advancements, including segmented PCM blocks, have improved heat absorption rates and uniform temperature distribution, achieving a 32.59% increase in heat absorption compared to traditional systems [34]. Furthermore, hybrid solutions combining PCMs with fins or water tubes have demonstrated superior performance under varying ambient conditions, ensuring optimal battery operation [12]. Overall, the application of PCMs in battery thermal management systems represents a promising avenue for enhancing battery safety and longevity [35].

The integration of phase change materials (PCMs) with active cooling systems, such as liquid cooling, presents a promising approach to enhance thermal efficiency in various applications. While PCMs are effective in managing thermal loads due to their high latent heat, challenges persist, including the selection of materials with appropriate melting points and the degradation of PCMs after multiple phase change cycles [36], [37]. Additionally, the thermal conductivity of PCMs is often low, which can hinder heat transfer efficiency; thus, innovative solutions like dynamic phase change materials (dynPCMs) and metal foam structures have been proposed to improve performance by reducing the thickness of the liquid layer during melting [36], [38]. Furthermore, the use of macro-encapsulation techniques and topology optimization can enhance the effectiveness of PCMs in building applications, allowing for better integration with renewable energy sources and advanced control systems [39]. Overall, addressing these challenges is crucial

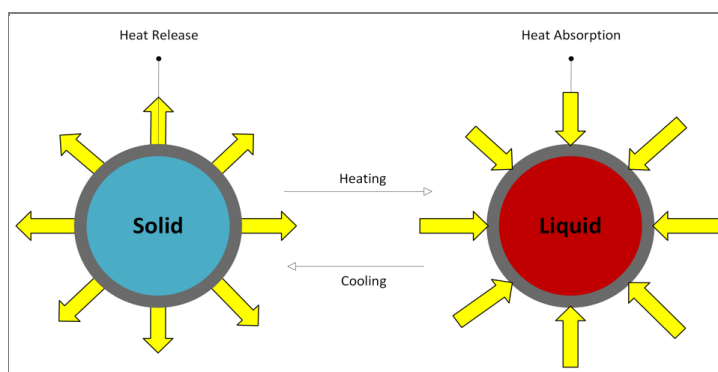


Figure 4.
Illustration of PCM
cooler working
principle [37]

for maximizing the potential of PCMs in both passive and active thermal management systems. Phase-Change Materials (PCMs) Cooling employs materials that absorb heat during the phase change. It has passive cooling and no active components, however its heat dissipation capacity is limited.

2.1.4. Thermoelectric cooling

Thermoelectric cooling, leveraging the Peltier effect, is increasingly recognized for its effectiveness in battery thermal management systems (BTMS), particularly in electric vehicles (EVs) and mobile devices. This technology allows for precise temperature control, enabling targeted cooling without impacting the entire system, which is crucial for maintaining battery performance and longevity [40]. Studies indicate that thermoelectric coolers (TECs) outperform traditional cooling methods, such as forced convection, by providing significant cooling effects with lower energy wastage [41]. Additionally, innovative combinations of TECs with other cooling technologies, like Stirling engines and thermoelectric generators, have been explored to enhance

efficiency and reduce power consumption [42]. Comparing natural convection, forced-convection, and thermoelectric generator (TEG) cooling methods, the TEG system demonstrates the highest effectiveness, achieving a temperature reduction of 16.44% at a 3C discharge rate [43]. However, while TECs can improve power output in smaller solar panels, their high power consumption relative to the benefits limits their application in larger systems [44]. Overall, the integration of TECs in BTMS presents a promising avenue for optimizing thermal management in various applications, Figure 5 shows a diagram of battery cooling with TEC.

Thermoelectric efficiency remains constrained by a low coefficient of performance (COP) and high electrical power demands, which can strain battery systems. Current research is focused on enhancing thermoelectric materials, particularly through the development of nanocomposite and polymer-based materials, which have shown promise in improving the thermoelectric figure of merit (ZT) by optimizing properties such as the Seebeck coefficient and electrical conductivity [45], [46]. Innovations in material science, including chemical doping and nanostructuring, are pivotal in advancing these materials for practical applications [46], [47].

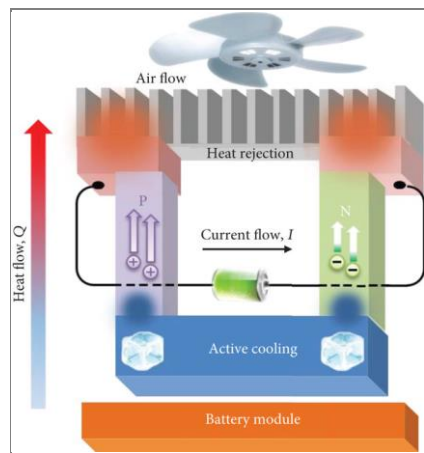


Figure 5.
Diagram of Peltier
effect in battery
thermoelectric
cooling [43]

Furthermore, integrating thermoelectric cooling with liquid cooling systems is being explored to leverage the strengths of both technologies, potentially leading to more efficient energy conversion and waste heat recovery solutions [47], [48]. Despite these advancements, challenges such as low energy conversion efficiency and high costs persist, necessitating ongoing research to enhance the economic viability of thermoelectric systems [49]. Thermoelectric Cooling (Peltier Effect) uses thermoelectric modules to transfer heat away from the battery. This cooling technology provides compact and accurate temperature control, no moving parts, but limited cooling capacity and inferior energy efficiency.

3. Comparative Analysis

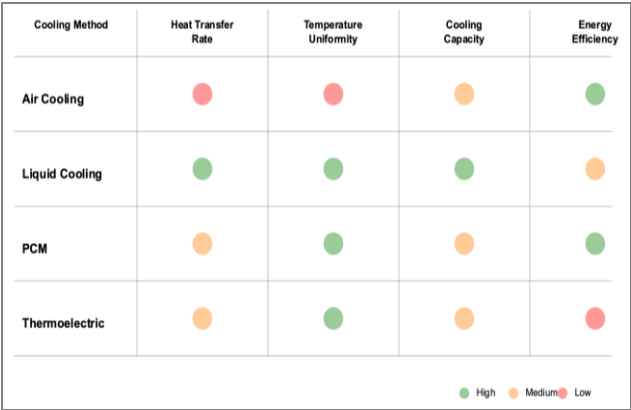
3.1. Thermal Efficiency

Thermal efficiency is critical in evaluating battery cooling technologies, with liquid cooling emerging as the most effective method due to its superior heat absorption and dissipation capabilities, particularly in high-capacity battery systems that generate significant heat. In this study, the streamline channel cold plate achieved a maximum surface temperature of 307 K with a temperature difference of only 3.15 K and a low pressure drop of 377.16 Pa, indicating excellent thermo-hydraulic performance. Comparative analysis further shows that indirect liquid cooling with cold plates can operate reliably within 307–310 K, maintaining higher thermal efficiency and more stable hydraulic characteristics than air cooling (ΔT often >10 K, lower heat transfer coefficient) or direct refrigerant cooling (effective but with higher pressure losses) [2], [9]. In contrast, air cooling exhibits lower efficiency, especially under high ambient temperatures, due to air's limited specific heat capacity [9]. Recent advancements in hybrid cooling systems, which combine multiple cooling methods, have shown promise in enhancing thermal management efficiency, thereby improving battery performance and longevity. For instance, PCM–air hybrid systems have demonstrated the ability to maintain a maximum cell temperature below 40 °C with a temperature difference (ΔT) under 3 °C while reducing auxiliary power consumption by up to 59%. In contrast, PCM–liquid hybrid systems achieve even higher thermal efficiency, with experimental results showing reductions of maximum temperature to below 39 °C and improved temperature uniformity (<3 °C), while maintaining low hydraulic resistance due to optimized microchannel cold plates (pressure drop typically <400 Pa). Comparative analysis highlights that hybrid PCM–liquid cooling provides faster heat removal and better temperature uniformity than PCM–air, with thermal efficiency improvements of 20–35% depending on load conditions [14], [17]. Additionally, immersion cooling techniques utilizing dielectric fluids have demonstrated significantly improved heat transfer rates compared to traditional air cooling, further emphasizing the importance of selecting appropriate cooling methods for optimal battery thermal management [50]. Figure 6 shows a comparison of the thermal efficiency of various cooling methods.

Thermoelectric cooling systems, while offering precise temperature control, often face challenges related to power consumption and cooling capacity. Recent advancements, such as the integration of thermoelectric generators (TEGs) with thermoelectric coolers (TECs), have shown promise in enhancing efficiency by converting waste heat into usable energy, thereby reducing overall power requirements and improving cooling performance. Experimental results indicate that at a 3C discharge rate, a pure TEG system can limit the maximum battery temperature to 65.43 °C, significantly lower than forced convection cooling (70.52 °C) and natural convection cooling (78.30 °C). Moreover, collaborative PCC (Parallel Collaborative Cooling) systems achieve an average cooling capacity improvement of 18% with COP values up to 1.12, while VCC (Voltage Collaborative Cooling) systems further enhance cooling capacity by 33% and reach a maximum COP of 1.339 with a thermo-electric conversion efficiency (ψ) of 0.188. From a thermal-hydraulic perspective, the integration reduces thermal gradients ($\Delta T \leq 5\text{ }^{\circ}\text{C}$) and maintains stable operation with power consumption ratios (RPe) ranging from 0.42–1 in PCC to 1.07–1 in VCC, highlighting their superiority in both cooling efficiency and energy utilization compared to conventional TEC-only systems [43], [51]. Additionally, the development of Distributed Transport Properties (DTP) technology has enabled TECs to achieve lower operating temperatures and significantly higher heat pumping capacities, which is crucial for applications requiring deep cooling [52].

Combining these thermoelectric systems with liquid cooling methods or phase change materials (PCMs) can further optimize thermal management, leveraging the strengths of each technology to meet intensive heat management needs effectively [53]. This multifaceted approach not only enhances cooling efficiency but also addresses the limitations of conventional systems, making it a viable solution for modern thermal management challenges.

Figure 6. Comparison of thermal efficiency of various cooling methods



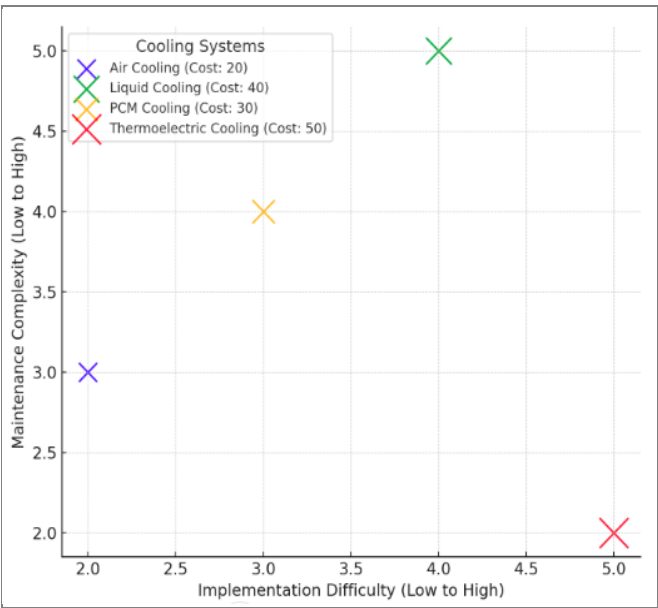
3.2. Design Complexity

Air cooling systems for electric vehicles (EVs) are characterized by their simplicity and cost-effectiveness, primarily utilizing fans or vents, which facilitate easy implementation and maintenance [54]. Research indicates that while air cooling can be effective for certain components, such as batteries, it may not suffice for high-power electronic components, which require more robust cooling solutions due to their operational demands [55]. In contrast, fluid cooling systems, although more complex, incorporate components like pumps, heat exchangers, and reservoirs, which enhance thermal management but complicate both initial design and

ongoing maintenance [56]. The choice between these systems ultimately hinges on the specific cooling requirements of the vehicle's components, with air cooling being less feasible for high-performance applications, necessitating the adoption of liquid cooling systems for optimal performance and longevity [55].

PCM-based methods for battery thermal management systems (BTMS) are recognized for their simplicity, as they do not necessitate active components like pumps or fans, making them cost-effective and easier to implement [57]. However, the integration of PCM with battery modules

Figure 7. Complexity matrix of various cooling systems



requires meticulous design to ensure uniform heat distribution and effective cooling, as uneven melting can lead to temperature irregularities [34]. While PCM systems can significantly reduce battery temperatures—demonstrating a drop from 113 °C to around 65 °C in simulations [11]—they may not suffice under extreme conditions, necessitating hybrid solutions that combine passive and active cooling methods, such as thermoelectric cooling [9], [57]. Thermoelectric systems, while effective, introduce complexity due to the need for dedicated modules and electronic controls to manage the Peltier effect, contrasting with the more straightforward passive PCM approaches [9], [13]. Thus, while PCM offers a reliable cooling mechanism, its integration with advanced technologies is essential for optimal performance in high-demand applications. The comparison between implementation complexity and maintenance complexity is represented in the Figure 7.

3.3. Implementation Cost

The cost of implementing cooling technology varies greatly depending on the method used. Air cooling is the most economical option as it uses simple components with low manufacturing costs. However, the effectiveness of this method is limited to applications with low to moderate thermal requirements, making it less ideal for high-performance electric vehicles.

Liquid cooling systems, while effective, incur higher costs due to the necessity of additional components such as pumps, heat exchangers, and specialized fluids, alongside significant development and maintenance investments [58]. In contrast, phase change materials (PCMs) present a more cost-effective initial solution, leveraging their high energy storage density and isothermal behavior to enhance cooling efficiency [59]. However, the operational costs can escalate due to the need for specialized materials and the replacement of PCMs after repeated phase change cycles [60]. For instance, while PCMs can reduce cooling system size by up to 12% and increase server capacity without additional cooling load, their thermal conductivity limitations necessitate careful selection and potential enhancements for optimal performance [61]. Ultimately, while PCMs offer lower upfront costs, their long-term viability must consider material longevity and replacement expenses [62].

Thermoelectric cooling (TEC) systems, while offering efficient cooling without refrigerants, face significant challenges due to high costs associated with quality thermoelectric modules and complex control systems [63], [64]. Recent advancements in thermoelectric materials, particularly the exploration of alternatives to traditional Bi₂Te₃ alloys, present opportunities for cost reduction and improved efficiency [65]. Additionally, integrating phase change materials (PCM) with fluid systems can enhance cooling performance, although this approach introduces design complexities [64]. The economic viability of TEC systems can be further improved through optimized designs that balance thermal performance and manufacturing costs, particularly by reducing heat exchanger expenses and enhancing thermal contact efficiency [66]. Thus, while TEC remains costly, ongoing research and innovative combinations of cooling methods may lead to more accessible and efficient solutions in the future.

3.4. Performance Over a Wide Range of Environmental Conditions

The performance of cooling systems in electric vehicles is significantly influenced by environmental conditions, particularly when comparing air and liquid cooling methods. Air cooling, while cost-effective and simple, struggles in extreme heat, leading to potential battery overheating due to its limited heat dissipation capabilities [67]. In contrast, liquid cooling systems demonstrate superior thermal management, maintaining battery temperatures within optimal ranges even in high ambient temperatures (up to 40 °C) [68]. Research indicates that liquid cooling can lower maximum battery temperatures by approximately 10 °C, showcasing its effectiveness in regulating thermal conditions [69]. Furthermore, the design of liquid-cooled plates and the choice of coolant are critical, as they directly impact cooling efficiency and battery longevity [70]. Overall, liquid cooling systems provide a more stable and effective solution for managing battery temperatures under varying environmental conditions [71].

Phase Change Materials (PCMs) effectively manage short-term heat surges but can lose cooling capacity in prolonged hot conditions without re-cooling, as demonstrated in various studies. For instance, PCM-based thermoelectric (TE) systems can maintain low temperatures for extended periods, with one prototype sustaining temperatures below 5 °C for up to 7 hours without electricity [72]. However, the integration of PCMs with thermoelectric coolers enhances thermal performance, significantly reducing both hot and cold side temperatures, thus improving efficiency [73]. Despite these advantages, thermoelectric cooling systems, while providing

consistent cooling even in extreme conditions, require substantial power, which poses a challenge for electric vehicle designs [74]. Therefore, while PCMs offer a promising solution for thermal management, careful consideration of energy consumption is essential for sustainable applications [75].

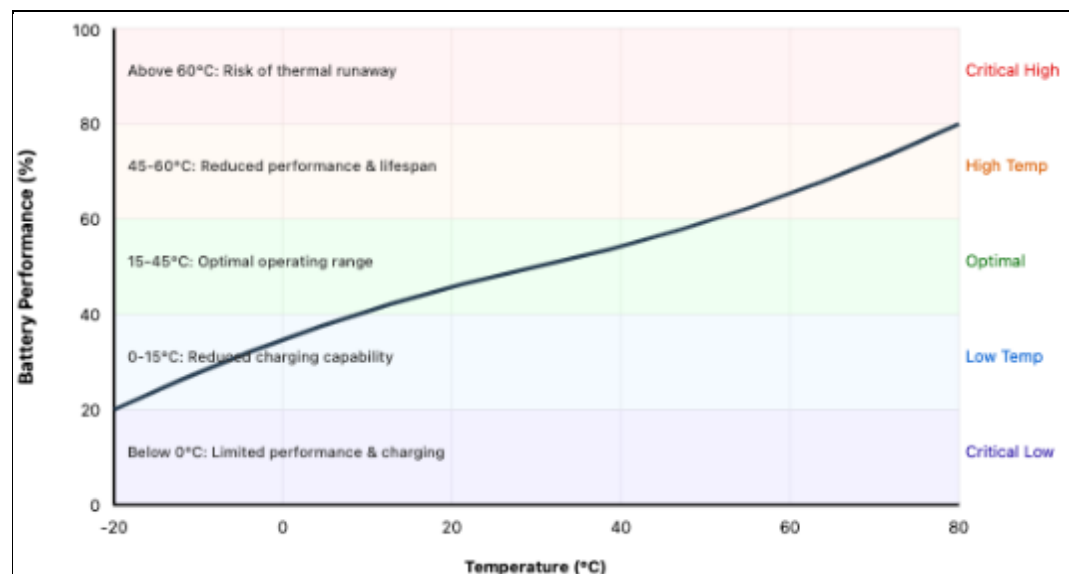
4. Technical Challenges

4.1. Heat Management

Heat management in battery cooling systems is critical due to the uneven heat distribution within battery modules, which can lead to capacity imbalances and accelerated degradation. Liquid cooling methods and phase change materials (PCM) have demonstrated superior temperature uniformity; however, challenges remain in achieving even cooling, particularly in complex module configurations. Integrated thermal management systems (IBTMs) that combine PCM with heating elements have shown promising results, maintaining temperature differences within 1.8 °C even under high cycling conditions (2C–1C at 40 °C ambient), capping the maximum module temperature at ≤ 52 °C over five continuous cycles, and recovering capacity to 92.1% (charge) and 93.3% (discharge) after preheating to the optimal low-temperature target of 10 °C. In contrast, external heating alone risks “false heating” because of high internal thermal resistance, underscoring the benefit of in-situ heating layers (PHF) embedded within CPCM [76]. Additionally, innovative cooling technologies, such as pulsating heat pipes and thermoelectric cooling, have been explored, revealing significant temperature reductions compared to traditional methods [77], [78]. Despite advancements, the need for further research into direct liquid cooling and hybrid systems persists to enhance the effectiveness of battery thermal management in electric vehicles [79]. Figure 8 shows the effect of temperature on battery performance.

The development of intelligent technology-based cooling systems is crucial for managing sudden heat spikes during fast charging cycles in electric vehicles (EVs). Effective thermal management is essential to maintain the optimal operating temperature of lithium-ion batteries, which is typically between 15 and 30 °C [80]. Advanced systems, such as automated fluid flow control and integrated thermal sensors, are being explored to enhance responsiveness and adaptability in cooling solutions. For instance, the integration of electric compressors and direct air heating systems allows for a balanced thermal management approach that addresses the complex demands of both the cabin and powertrain [81]. Additionally, adaptive control strategies, including microprocessor-based systems and machine learning techniques, are being investigated to optimize cooling performance and energy efficiency, demonstrating the potential for real-time adjustments based on varying operational conditions [82].

Figure 8. Distribution of battery performance against temperature showing the relationship between battery performance (%) and temperature variation (-20 °C to 80 °C)



The integration of cooling systems with battery module designs is critical for optimizing thermal efficiency in electric vehicles (EVs) while minimizing space and weight constraints. Recent research highlights various methodologies for enhancing battery thermal management systems (BTMS), including the use of advanced materials like graphene to improve thermal conductivity

[83]. For instance, liquid-cooled systems have been shown to effectively maintain battery temperatures within safe limits, even under high discharge rates, by utilizing innovative designs such as series-parallel hybrid channels [68]. Additionally, coupled cooling systems that combine air and liquid cooling have demonstrated superior performance in managing heat generation during operation [84]. The incorporation of phase change materials for latent heat storage further enhances thermal management efficiency, particularly in extreme temperature conditions [85]. Overall, these advancements underscore the importance of integrated thermal management solutions in the evolving landscape of EV technology [86].

4.2. System Design

The design of battery cooling systems for electric vehicles (EVs) must balance efficiency, reliability, and spatial constraints, with air cooling being simpler yet limited in capacity, while liquid cooling, though more effective, introduces complexity. Studies indicate that liquid cooling systems, particularly those utilizing advanced designs like variable temperature cooling and optimized channel configurations, significantly enhance thermal management by maintaining lower maximum temperatures and reducing temperature differentials within battery packs [17], [26]. For instance, a liquid cooling system can lower the maximum temperature from 48.73 °C to 30.75 °C, demonstrating superior performance compared to air cooling [26]. Additionally, integrating microcontrollers for real-time monitoring and adjustments can further optimize cooling efficiency, ensuring battery safety and longevity [87]. Overall, while liquid cooling systems require careful design to accommodate additional components, their benefits in thermal regulation and battery performance are substantial [88].

The design of battery thermal management systems (BTMS) is increasingly adopting a modular approach to enhance flexibility across various battery types and vehicle applications. This modularity allows for the rearrangement of cooling systems without necessitating a complete redesign, thereby accommodating diverse operational requirements [89]. Simulation software plays a crucial role in optimizing thermal designs early in the development process, significantly reducing the risk of costly errors and minimizing optimization time from over 200,000 seconds to approximately 46,000 seconds [90]. Additionally, effective thermal management is vital for maintaining battery performance, as temperature directly influences charging, discharging efficiency, and overall battery lifespan [91]. Recent studies have demonstrated that innovative designs, such as air-cooling systems with multiple inlets and outlets, can improve temperature uniformity and reduce energy consumption, further supporting the need for adaptable thermal management solutions [54].

5. Recent Innovations

5.1. Hybrid Cooling Technology

Hybrid cooling technology, particularly the integration of phase change materials (PCM) with liquid cooling systems, has emerged as a robust solution for enhancing thermal management in various applications, including lithium-ion batteries and downhole electronics. This approach leverages the thermal stability provided by PCM to absorb heat surges while the liquid cooling system ensures continuous heat removal, thus maintaining optimal operating temperatures. For instance, a hybrid system combining PCM with liquid microchannels has demonstrated significant effectiveness in suppressing thermal runaway in battery packs, keeping temperatures below critical thresholds [92]. Similarly, a hybrid thermal management system for downhole electronics has extended operational time significantly, reducing temperature differentials to enhance reliability [93]. Furthermore, experimental studies have shown that such hybrid systems can achieve remarkable heat flux removal rates and maintain stable temperature changes, underscoring their potential for high-performance applications. For instance, using a spray cooling–FPHP hybrid configuration with multi-nozzle arrays and optimized surface roughness ($R_a = 1.62 \mu\text{m}$), the maximum heat flux removal increased from 70 W/cm² to 90 W/cm² with a surface superheat of only 4.17 °C, achieving a heat transfer coefficient of 21.6 W·cm⁻²·K⁻¹ (28.6% enhancement). In addition, the system demonstrated exceptional thermal stability, with a temperature change rate below 0.015 °C/s and a total variation of just 0.9 °C within one minute, ensuring reliable operation of electronic components under high heat loads. As shown in Figure 9, the integration scheme highlights not only superior heat rejection capacity but also highly stable transient response, a combination that is challenging to achieve with conventional air or liquid

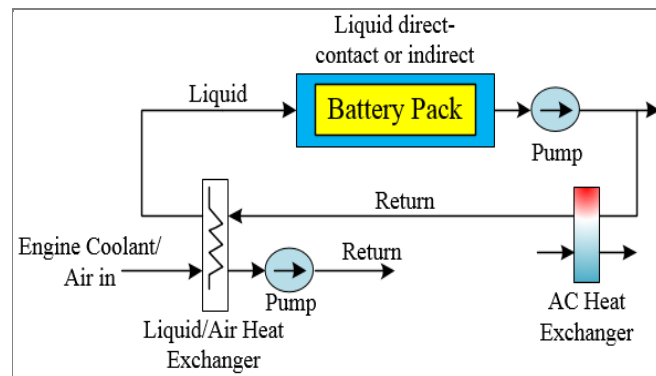
cooling alone [94], [95]. Overall, the synergy of PCM and liquid cooling presents a promising avenue for addressing intensive thermal needs across diverse fields.

The integration of thermoelectric cooling with liquid cooling systems in electric vehicles (EVs) enhances thermal management efficiency while reducing power consumption. Research indicates that combining these methods allows for precise temperature control of critical components, such as lithium-ion batteries, which are sensitive to temperature fluctuations. For instance, a study demonstrated that thermoelectric cooling, when paired with water cooling at optimal flow rates, can lower battery temperatures by 41-52% during discharge, significantly outperforming air cooling systems [96]. Additionally, a hybrid liquid cooling system utilizing both direct and indirect methods has shown to effectively manage heat distribution, maintaining battery temperatures below critical thresholds [97]. Furthermore, model predictive control strategies applied to thermoelectric systems have resulted in notable reductions in energy consumption and response times, underscoring the potential for improved thermal management in EV applications [98]. Overall, this combined approach not only enhances performance but also addresses safety concerns associated with high-power charging [99].

Hybrid cooling technologies increasingly incorporate renewable energy methods, enhancing energy efficiency and reducing reliance on conventional battery power. For instance, combined cooling, heating, and power systems can effectively integrate solar and geothermal energy, achieving a solar energy utilization rate of 79% and a comprehensive performance index of 69% when optimized for electrical load strategies [100]. Additionally, hybrid solar cooling systems, which combine photovoltaic and solar thermal collectors, have demonstrated significant energy savings, achieving a solar fraction of 0.85 and reducing fossil fuel consumption by 27% compared

to traditional systems [101]. Furthermore, solar vapor absorption refrigeration systems paired with conventional vapor compression systems have shown an 83% increase in coefficient of performance, significantly lowering carbon emissions [102]. These advancements illustrate the potential of hybrid systems to drive sustainable cooling solutions across various applications [103].

Figure 9.
Integrated hybrid
cooling system [95]

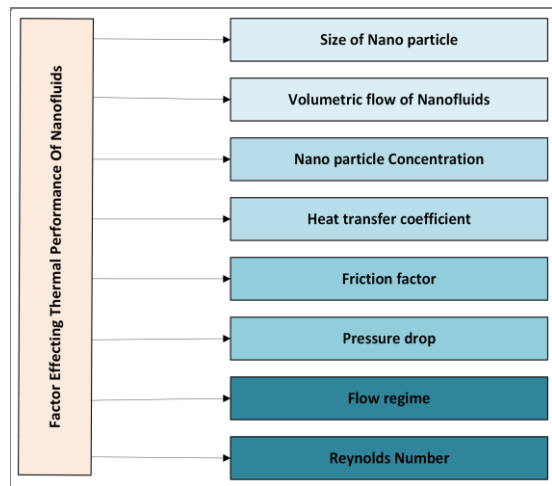


5.2. Nanotechnology Materials

Nanotechnology significantly enhances battery cooling systems, particularly through the use of nanofluids, which incorporate nanoparticles like metal oxides and graphene to improve thermal conductivity and heat transfer efficiency. Research indicates that these nanofluids can boost cooling performance by 20–30% compared to traditional coolants, with specific studies demonstrating even greater improvements. For instance, the integration of 1% v/v MXene nanoparticles with ester oil achieved a remarkable ~50% reduction in cell temperatures at 0.01 m/s, compared to pure water coolant at the same flow rate, and further improvements were observed with increasing flow velocity (up to 54% reduction at 1.0 m/s). Similarly, diamond-based nanofluids showed a 25.2% reduction in the temperature rise-to-discharge capacity ratio relative to water. However, nanofluids often suffer from long-term stability challenges, such as particle agglomeration, and require higher pumping power due to increased viscosity, which can offset part of their thermal advantages in large-scale battery thermal management systems [104], [105]. Additionally, ultrasonic-assisted nanofluid systems have been shown to maintain battery temperatures below 35.2 °C, enhancing uniformity and efficiency [106]. Overall, these advancements underscore the critical role of nanofluids in optimizing thermal management for lithium-ion batteries, ensuring safety and performance in electric vehicles [107]. The factors affecting the thermal performance of nanofluids are described in Figure 10.

Graphene-based materials significantly enhance passive cooling systems, particularly in thermal coatings and phase change materials (PCMs), due to their exceptional thermal conductivity and lightweight properties. For instance, a composite of expanded graphite, PCM, and graphene demonstrated a 26% temperature reduction in battery thermal management systems compared to conventional materials, effectively addressing issues like fluid leakage and low thermal conductivity [108]. Additionally, graphene's in-plane thermal conductivity, which can reach up to

Figure 10.
Factors effecting
thermal performance
of nanofluids [105]



5000 W/(m·K), has been shown to improve heat dissipation in photovoltaic panels, resulting in a 20% reduction in focal spot temperature and a 12% efficiency increase [109]. Furthermore, flexible graphene-based composites have been developed for chip cooling, achieving a thermal conductivity increase of 295% over pure paraffin wax, thus reducing thermal resistance and enhancing performance in electronic devices [110]. Overall, the integration of graphene in thermal management systems not only improves efficiency but also simplifies design, making it a promising solution across various applications [111].

5.3. Smart Systems (Smart Cooling)

Smart cooling systems for electric vehicle batteries utilize advanced sensors and control algorithms to optimize thermal management based on real-time conditions. These systems integrate thermal sensors within battery modules to continuously monitor temperature, enabling adaptive regulation of cooling mechanisms such as fluid flow and fan speed. For instance, model predictive control (MPC) strategies have been shown to enhance battery efficiency and lifespan by maintaining optimal temperature ranges and preventing overheating due to excessive ohmic losses [112]. Additionally, innovative designs combining liquid and air cooling methods have demonstrated improved temperature uniformity and reduced fluctuations, achieving a temperature difference of less than 2 °C across battery modules [113]. Overall, these smart systems are crucial for maximizing vehicle performance and ensuring battery safety and longevity [114], [115].

Smart cooling systems for electric vehicle (EV) batteries offer significant advantages by dynamically adjusting to thermal loads, thereby enhancing energy efficiency and maintaining optimal battery temperatures. These systems utilize a combination of active and passive cooling techniques, such as indirect cooling with vapor compression cycles and two-phase direct liquid cooling, which effectively manage heat generation during operation [77], [87]. The integration of microcontrollers allows for real-time monitoring and adjustments, ensuring that battery temperatures remain within safe limits, which is crucial for prolonging battery life and performance [87], [116]. Additionally, smart cooling technologies facilitate remote monitoring and diagnostics, providing users and manufacturers with critical thermal status information, which aids in troubleshooting and enhances overall system reliability [117], [118]. This holistic approach not only addresses the challenges of thermal management but also contributes to the sustainability of electric transportation systems.

5.4. Artificial Intelligence Integration

The integration of artificial intelligence (AI) is one of the leading innovations in battery cooling technology. AI is used to learn vehicle operation patterns and cooling needs through historical data analysis. With machine learning algorithms, the cooling system can predict future cooling needs and proactively organise cooling strategies. Artificial intelligence (AI) significantly enhances energy efficiency in cooling systems by optimizing power usage based on real-time environmental conditions and thermal loads. Machine learning algorithms, as discussed in various studies, enable predictive maintenance by identifying anomalies such as fluid leaks or sensor failures, which can prevent severe battery damage and operational disruptions [119], [120]. For instance, AI-driven systems can analyze sensor data to dynamically adjust cooling operations, ensuring optimal performance while minimizing energy consumption [121]. Additionally, the integration of AI in building automation systems allows for continuous monitoring and adjustment of energy usage, thereby improving occupant comfort and reducing carbon emissions [122]. This proactive management not only enhances system reliability but also contributes to broader sustainability goals by reducing the overall environmental impact of energy consumption in buildings [120]. The use of AI in cooling systems enables wider integration with the electric vehicle ecosystem, such as connectivity with battery management systems (BMS) and IoT platforms, to create a holistic and integrated thermal management solution.

6. Discussion

6.1. Comparison of Cooling Methods

Battery cooling methods exhibit distinct advantages and disadvantages, significantly influenced by application requirements and operational conditions. Air cooling, while cost-effective and straightforward, struggles with thermal efficiency, particularly in high-temperature environments, leading to potential overheating and capacity loss in lithium-ion batteries, as ΔT often exceeds 6 °C for large packs [25]. Liquid cooling systems demonstrate superior thermal management by maintaining stable battery temperatures (15–35 °C) and ΔT below 6 °C even under high workloads, effectively mitigating risks such as thermal runaway and uneven temperature distribution [25], [29]. However, they introduce complexity and higher costs, and require design refinements—for example, integration of fans into liquid-cooled plates has been shown to improve cooling rate by 0.59 K/min, a 23% enhancement in uniformity [123]. Hybrid approaches, integrating air and liquid cooling, or spray-assisted forced-air methods, further enhance performance; for instance, optimized HFE spray cooling reduced the maximum cell temperature by about 6 °C and temperature non-uniformity by 4 °C compared with dry air cooling [124]. Overall, the choice of cooling method must balance thermal performance, cost, energy consumption, and complexity to meet specific operational demands.

PCM-based cooling systems effectively manage short-term heat spikes by absorbing and releasing thermal energy during phase transitions, thus maintaining stable temperatures without additional energy consumption [11], [38]. For instance, without PCM cooling, lithium-ion battery modules can reach temperatures as high as 113 °C, whereas paraffin-based PCM reduces the maximum temperature to ~65 °C—a 40–50 °C improvement [11]. The integration of copper metal foam further enhances PCM performance, with the vertical foam configuration reducing melting time by up to 41% and lowering maximum temperature by ~96.8 °C compared to baseline designs [38]. Hybrid HS-PCM systems also show improved durability, where increasing PCM thermal conductivity from 0.05 to 0.8 W/(m·K) extended working duration from 22 to 24 minutes [125].

These results confirm that PCM-based systems can substantially improve thermal safety and reliability under cyclic loads. However, their effectiveness is inherently limited by the latent heat storage capacity and saturation of the material, making them less effective under prolonged or continuous high loads. In contrast, thermoelectric cooling offers precise and continuous temperature control but at the expense of high power consumption and cost, with COP values typically ≤ 1.3 , which restrict scalability in large-scale applications [126]. Therefore, while PCM systems present a sustainable and passive cooling solution, careful selection of melting temperature, thermal conductivity, and structural integration (e.g., foams, plate numbers) is crucial to optimize their performance and mitigate limitations. The battery cooling distribution map in Figure 11 visually summarises this trade-off, where PCM scores highly in energy efficiency and reliability, but lower in complexity and long-term sustainability compared to liquid or thermoelectric cooling.

Hybrid cooling methods effectively integrate various technologies to enhance thermal efficiency while addressing design complexities. For instance, a dual-thermoelectric-liquid hybrid system for CPU cooling demonstrated a significant reduction in temperature to 42 °C, achieving a

coefficient of performance of 0.039 through optimized parameters [127]. Similarly, a hybrid flow configuration improved regenerative cooling performance by optimizing temperature distribution and increasing fuel conversion ratios under varying conditions [128]. In superconducting dipole magnets, a hybrid scheme combining forced flow and conduction cooling allowed operation at 320 A, significantly outperforming traditional methods [128]. Additionally, a hybrid evaporative cooling system utilizing latent-heat thermal energy storage effectively reduced ambient air

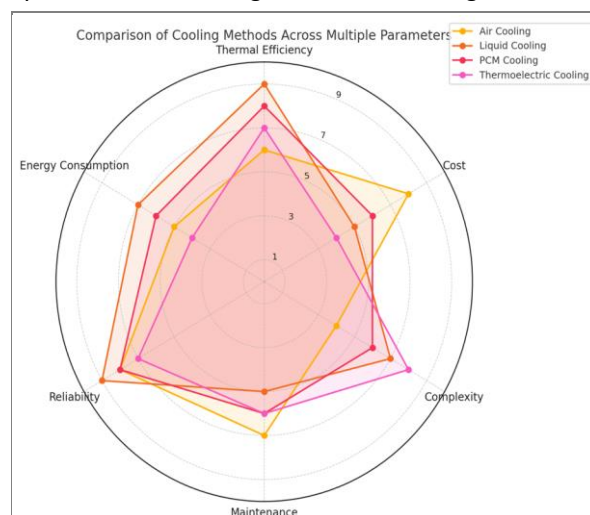


Figure 11.
Spider chart of cooling
method comparison

temperature and humidity, showcasing the potential for energy efficiency in commercial settings [129]. Lastly, a dual-cooling system for photovoltaic modules improved efficiency by 11.23% through innovative cooling techniques [130]. These examples illustrate the promise and challenges of hybrid cooling solutions across diverse applications.

6.2. Advantages and Disadvantages of Each Technology

Air cooling systems in electric vehicles (EVs) are favored for their simplicity and cost-effectiveness, making them suitable for moderate thermal requirements. However, they suffer from limited thermal efficiency and are heavily influenced by ambient temperatures, where ΔT often exceeds 6–10 °C in large battery packs, leading to faster capacity fade [15], [124]. In contrast, liquid cooling systems, while more complex and expensive, provide superior thermal management essential for high-capacity batteries and demanding energy needs. For example, indirect cooling using ethylene glycol–water (EGW) solutions has been shown to reduce maximum cell temperature by 5–7 °C and improve temperature uniformity while lowering pressure drops compared to direct liquid flow [131]. Liquid cooling can also reliably sustain >2C discharge rates without exceeding the safe operating window (15–35 °C). A comparison of various types of cooling is summarised in Table 1.

Phase Change Materials (PCMs) offer energy-efficient passive thermal management by absorbing heat surges through latent heat transitions. Simulation studies show paraffin-based PCM can lower T_{max} from 113 °C (no cooling) to ~65 °C, a 40–50 °C reduction [11]. When enhanced with metal foams or nanoparticles, PCMs can achieve faster melting (up to 41% reduction in melting time) and more uniform distribution [38], [132], [133]. However, PCM systems saturate within ~30 minutes of continuous load and require auxiliary systems (fans, liquid loops, or fins) for extended operation. Thus, while PCM systems manage spikes effectively ($\Delta T \leq 3$ °C), they are less effective for long-duration or high-C-rate scenarios.

Thermoelectric cooling (TEC) systems offer precise temperature control, with optimized collaborative systems (VCC/PCC) achieving COP up to 1.3 [126], [134]. They are well-suited for localized cooling and maintaining tight ΔT margins, but come at the expense of high parasitic energy use—2–3× higher than PCM—and greater system cost, which hinders scalability in large EV battery packs.

Hybrid technologies combine the strengths of multiple methods to balance efficiency and reliability. For example, integrating a hybrid energy storage unit with CCHP systems improved system efficiency by up to 21.7% through optimized control strategies [135]. Similarly, industrial hybrid systems with redundancy achieved 44% higher reliability at only 5% additional cost [136], while hybrid energy plants integrating solar, CHP, and heat pumps reduced life-cycle energy demand by ~12% [137]. In battery applications, hybrid approaches (liquid + PCM, or liquid + TEC) can maintain $\Delta T \leq 3$ –4 °C, extend lifespan, and reduce energy use through intelligent control.

Table 1.
Comparative summary of
major EV battery
cooling methods

Cooling Method	ΔT Reduction / Thermal Range	COP / Energy Use	Cost	Complexity	Advantages	Limitations
Air Cooling	$\Delta T \sim 5$ –10 °C	Low COP, high dependence on ambient	Low	Low	Simple, low cost, lightweight	Poor heat transfer, ineffective in tropical climates
Liquid Cooling	$\Delta T \sim 15$ –20 °C; maintains 30–35 °C	Medium COP, efficient under high load	High	High	High efficiency, uniform temperature	Expensive, leakage risk, heavy
PCM Cooling	ΔT reduction up to 40–50 °C	Passive, no external energy	Medium	Low	Absorbs heat spikes, compact	Saturates under continuous load, low conductivity
Thermoelectric (TEC)	$\Delta T \sim 10$ –15 °C	COP ≤ 1.3 , high energy demand	High	Medium	Precise control, compact, no moving parts	High power use, costly, limited scalability
Hybrid (PCM + Liquid, PCM + TEC)	ΔT reduction up to 35%; uniform $\Delta T \leq 3$ °C	Higher efficiency than standalone	Medium–High	High	Combines strengths, adaptive to load	Still lab-scale, complex integration

6.3. Projections of Future Developments

Going forward, cooling technology is projected to increasingly integrate nanotechnology and artificial intelligence (AI) materials. Advanced materials such as graphene and nanofluids will be

used to improve heat transfer efficiency and reduce power requirements. In addition, AI-based smart systems will enable more adaptive heat management, with machine learning algorithms that predict cooling needs based on vehicle usage patterns. Thermoelectric cooling systems, powered by renewable energy sources, are emerging as a promising technology to reduce environmental impacts and enhance energy efficiency. These systems, which operate on the principles of the Seebeck and Peltier effects, offer significant advantages over traditional HVAC systems, including zero greenhouse gas emissions and cost efficiency, making them suitable for small and micro applications [138]. The integration of thermoelectric devices with renewable energy sources such as solar photovoltaic systems and waste heat recovery systems further enhances their potential, allowing for direct energy conversion and sustainable cooling solutions [139]. Recent advancements in thermoelectric materials, particularly through nanostructural doping to increase the Figure of Merit (ZT), have improved system efficiency by reducing lattice thermal conductivity and increasing the power factor. Moreover, the development of thermoelectric-based battery thermal management systems demonstrates the technology's capability to optimize the operating temperature of lithium-ion batteries, thereby improving cooling performance and energy consumption balance [140]. These systems are increasingly modular and space-saving, facilitating better integration with modern battery management systems and enabling their application in diverse settings, including solar-driven air-conditioning systems [141]. As research continues to enhance the thermal management techniques and material properties of thermoelectric coolers, their role in sustainable energy solutions is expected to grow, contributing to reduced reliance on fossil fuels and improved environmental conditions.

7. Conclusion

This comprehensive review explores the advancements and challenges in battery cooling technologies for electric vehicles, highlighting the critical role of thermal management in optimizing battery performance and ensuring safety. It delves into a wide range of cooling systems, from traditional air and liquid cooling to innovative approaches such as phase change materials (PCMs) and hybrid systems, providing an in-depth analysis of their efficiency, feasibility, and technological potential. By examining the integration of smart technologies, nanotechnology-enhanced solutions, and renewable energy-based methods, this review bridges the gap between current practices and future innovations in sustainable and intelligent cooling solutions for electric vehicles. From the review that has been done, the things that can be concluded are:

Key Findings Summary: The review reveals that while traditional air cooling systems offer simplicity and cost-effectiveness, they demonstrate limited thermal efficiency for high-performance electric vehicle applications. Liquid cooling systems, though more complex and expensive, provide superior thermal management capabilities, particularly in maintaining optimal battery temperatures and preventing thermal runaway. Phase Change Materials (PCMs) show promise in passive thermal management but face limitations in thermal conductivity and long-term stability. Hybrid cooling solutions, combining multiple cooling methods, have emerged as the most effective approach, with studies showing significant improvements in thermal efficiency and temperature uniformity, particularly when integrating PCMs with liquid cooling systems or thermoelectric devices.

Technological Implications: The advancement in battery cooling technologies has profound implications for the electric vehicle industry and sustainable transportation. The development of more efficient cooling systems directly impacts battery performance, longevity, and safety, enabling faster charging capabilities and extended vehicle range. The integration of smart cooling systems with artificial intelligence and real-time monitoring capabilities allows for dynamic thermal management, optimizing energy consumption and reducing operational costs. Furthermore, the emergence of nanotechnology-enhanced cooling solutions, particularly through the use of nanofluids and graphene-based materials, has demonstrated significant improvements in heat transfer efficiency, potentially revolutionizing thermal management systems in electric vehicles.

Future Research Directions: The field of battery cooling technology is moving toward more integrated and intelligent solutions, with several key areas requiring further investigation. Research efforts should focus on developing more efficient and cost-effective hybrid cooling systems, particularly those incorporating renewable energy sources and advanced materials. The optimization of artificial intelligence algorithms for predictive thermal management and the enhancement of nanotechnology-based cooling solutions represent crucial areas for future study. Additionally, research into improving the long-term reliability and stability of PCM-based systems,

alongside the development of more energy-efficient thermoelectric cooling solutions, will be essential for advancing the field. This research trajectory suggests a continued emphasis on sustainable, intelligent, and highly efficient cooling technologies for next-generation electric vehicles.

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Authors' Declaration

Authors' contributions and responsibilities - Muhammad Untung Zaenal Priyadi (Data curation; Writing - original draft;), Adhes Gamayel (Conceptualization; Formal analysis), Ganesha Tri Chandrasa (Methodology; Writing - Visualization), Eka Rakhman Priandana (Writing - review & editing, Resources), Heri Nugraha (Writing - review & editing, Formal analysis), Imaduddin Haq (Investigation; Formal analysis), Panca Kurniawan (Writing - review & editing).

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