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Advanced Thermal Management Systems for Performance Optimization and Lifespan Extension in Electric Vehicles

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ABSTRACT :

Electric-vehicle (EV) battery performance, safety and service life depend strongly on the operating temperature and temperature uniformity of the battery pack. Heat generated by electrochemical reactions, internal resistance and reversible entropic effects must be removed effectively; otherwise elevated or non-uniform cell temperatures accelerate ageing, reduce available power, create cell-to-cell imbalance and increase safety risks. This review consolidates four related literature syntheses into a single assessment of battery thermal management systems (BTMS) for EV applications. It covers air cooling, indirect liquid cooling, direct immersion and spray cooling, phase-change materials (PCMs), heat pipes, thermoelectric cooling (TEC) and hybrid systems, and extends the discussion to machine-learning and model-predictive thermal control, low-temperature preheating, cell-to-pack cooling with mechanical protection, charging infrastructure, and life-cycle and recycling considerations. More than twenty published studies are summarised with their reported values retained as supplied. Active liquid-based approaches reduced peak temperature and temperature variation under high discharge rates (for example, a simulated 48 V LFP pack fell from 330.71 K to 306.41 K at 8C), while air cooling remains attractive for simple, lower-heat-load systems but a natural-inlet 5S5P pack reached 126 °C at 3C. Thermoelectric studies reported strong cooling effects (a 55 °C to 12 °C surface-temperature drop) at an efficiency cost (COP of 1.09 in a zonal prototype), and a PCM–TEC arrangement with axial fins lowered mean battery temperature from 85 °C to 48 °C. Production footprints of 58–92 kg CO -eq/kWh for lithium-ion cells and a 61% lower CO -equivalent burden for an EV scenario versus an ICEV-only future place thermal design in a wider sustainability context. Because the studies differ in cell format, boundary conditions and metrics, their numerical results are not directly comparable. The review identifies the need for standardised comparative testing and integrated, multi-objective BTMS design that balances thermal performance with pumping power, auxiliary energy, mass, cost, reliability, safety and environmental impact.

Keywords: electric vehicle; lithium-ion battery; battery thermal management system; air cooling; liquid cooling; immersion cooling; thermoelectric cooling; phase-change material; model predictive control; fast charging; life-cycle assessment; battery safety.

Introduction

The transition towards electric mobility is driven by the need to reduce greenhouse-gas emissions, lower local exhaust emissions, improve urban air quality and diversify transport energy sources [2], [3]. Battery electric vehicles rely on rechargeable packs as their principal energy store, and lithium-ion technology is widely used because of its comparatively high energy density, good efficiency and suitable cycle life. The battery is central to vehicle range, acceleration, charging time, cost, safety and durability, yet battery cells are sensitive to temperature: electrochemical behaviour, internal resistance, charge acceptance and ageing rate all vary with operating temperature and with differences between cells.

A pack contains many cells in series and parallel, and during operation cells experience different current distributions, cooling conditions and local heat-transfer resistances, so one cell may run hotter than another. Excessive temperature accelerates side reactions, capacity fade and degradation; low temperature increases internal resistance, reduces power capability and, when charging, can promote lithium plating. Temperature non-uniformity also causes unequal ageing and reduces the usable capacity of the whole pack. A battery thermal management system (BTMS) is therefore required to hold cells within a suitable temperature range and to limit temperature differences across the pack during acceleration, regenerative braking, normal driving, fast charging and changing ambient conditions, without consuming excessive energy or adding unacceptable mass, cost and complexity.

Beyond the pack itself, thermal design interacts with the wider EV ecosystem: charging strategy and infrastructure, power-electronics and busbar heating, battery production footprint and end-of-life recovery. This paper therefore combines four complementary literature syntheses to give one coherent view from heat generation, through cooling technologies and intelligent control, to system-level and life-cycle considerations.

Objectives and scope

The objectives are to: (i) explain the main sources of heat generation in lithium-ion batteries; (ii) describe the major EV battery cooling methods, including thermoelectric and hybrid approaches; (iii) compare their advantages, limitations and reported performance; (iv) discuss control, charging, structural and sustainability aspects that influence BTMS selection; and (v) identify research directions for safe, efficient and durable battery packs. The paper is a literature review and does not claim new experimental or numerical results.

Review Scope and Methodology

This is a narrative technical review built from four sets of source material assembled by the authors for their term-paper and review projects: (a) research-study notes and numerical findings on cylindrical NMC and LFP cell packs, dielectric-liquid and spray cooling, cold plates and air-cooled packs; (b) a ten-paper literature-review table on thermoelectric, air-cooled, oil-cooled, PCM–TEC hybrid and life-cycle-assessment (LCA) work; (c) a ten-study record on battery sustainability, recycling, charging control, machine-learning thermal management, preheating, electrical components and cell-to-pack design; and (d) a general BTMS synthesis with data-driven and EV-deployment context. Studies that appeared in more than one source (for example the Degen et al. LCA and the ensemble-learning study of Naresh and Ayyappa) are merged and cited once.

The studies were grouped into five themes: cooling technologies (Sections 4–5), pack-level reported findings (Section 6), intelligent control and charging (Section 7), structural and electrical safety (Section 8), and sustainability and deployment (Section 9). Reported numerical values are reproduced as supplied and are not normalised across models, chemistries, operating conditions or system boundaries. Where a source record does not identify a software package, test condition, journal volume, page range or DOI, this information is not inferred; the reference list flags records that require bibliographic verification before journal submission.

Battery Heat Generation and Thermal Requirements

Sources of heat generation

Battery heat generation is commonly associated with irreversible and reversible contributions. Irreversible heat arises mainly from ohmic resistance and electrochemical polarisation and increases with current. Reversible heat is associated with entropy changes during the electrochemical reactions and may either add or absorb heat depending on the state of charge and operating condition. Additional heat may arise from non-uniform current distribution, contact resistance and ageing-related growth of cell impedance. A simplified engineering representation is

$$Q = I^2R + I \cdot T \cdot (\partial U/\partial T) \qquad (1)$$

where Q is the heat-generation rate, I the current, R the internal resistance, T the absolute temperature and $\partial U/\partial T$ the entropic coefficient of the open-circuit voltage. Because the irreversible term scales with I^2, higher C-rates raise heat generation sharply, which explains the strong C-rate dependence seen in the studies reviewed below.

Factors influencing battery temperature

The thermal response of a pack is influenced by charge or discharge rate (C-rate), current magnitude, cell chemistry and geometry, state of charge, internal resistance, ambient temperature, cooling-fluid properties, coolant flow rate and inlet temperature, channel geometry and thermal contact resistance. Closely packed cells can restrict airflow and create local hot spots if the cooling arrangement is not designed carefully.

Requirements of an effective BTMS

An effective BTMS should control the maximum cell temperature, minimise the temperature difference between cells, respond to transient heat loads and maintain performance over the vehicle life. It should also be energy-efficient, lightweight, compact, affordable, serviceable and compatible with battery materials. For liquid and immersion systems, leakage prevention, electrical insulation, corrosion control, coolant stability and end-of-life handling are further design considerations.

Battery Thermal Management Techniques

Figure 1 organises the main BTMS approaches discussed in this review into passive, active and hybrid families, with a supervisory control layer that coordinates them. Each method involves trade-offs in heat-transfer capability, weight, packaging, cost, reliability and parasitic energy consumption.

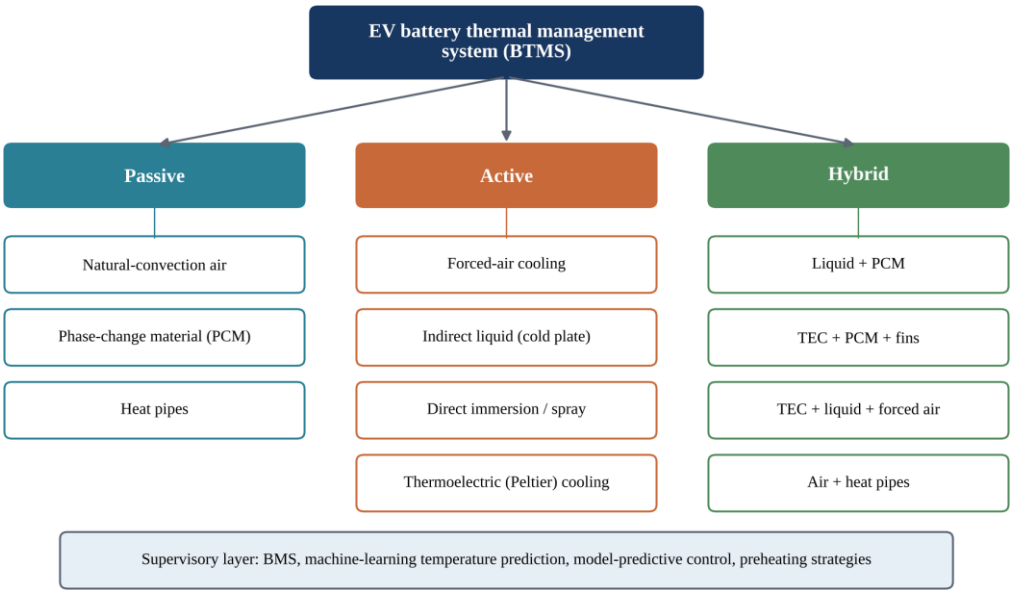


Figure 1. Classification of EV battery thermal management approaches and the supervisory control layer.

Air cooling

Air cooling passes ambient or conditioned air over the cells or through channels between them, using buoyancy (natural convection) or fans and blowers (forced convection). It is mechanically simple, light and economical and avoids coolant-leakage risk, but air has low heat capacity and thermal conductivity. High airflow rates may be needed at elevated C-rates, increasing fan power and noise, and poor duct design can cause uneven flow and temperature non-uniformity. Reported results show a strong dependence on C-rate and airflow velocity. In a 5S5P 18650 pack simulation [27], the maximum temperature with a natural circular inlet rose from 32.2 °C at 0.5C to 126 °C at 3C (Figure 3a). In a Formula Student pack study combining CFD and experiment [8], the best case occurred at an inlet velocity of about 17 m/s, holding battery temperature within about 40–50 °C, with simulation and experiment differing by about 4.256%. In a Peltier-hybrid modelling study at 1C charging [7], air cooling needed a very high velocity of about 47.5 m/s to maintain a 313 K limit. Raising air velocity improves convective heat transfer but raises fan energy and does not by itself guarantee uniform cooling.

Indirect liquid cooling

Indirect liquid cooling circulates a coolant, commonly a water–glycol mixture, through cold plates, tubes or channels thermally connected to the cells, and rejects the heat through a radiator or heat exchanger. Liquid systems offer high heat capacity and can remove heat more effectively than air in compact packs and under high heat loads. Their performance depends on channel geometry, flow distribution, flow rate, inlet temperature, pressure drop and cell-to-plate thermal contact, and the design must balance heat transfer against pump power, mass, complexity, leak prevention and serviceability. An oil-cooling case in a simulation study [7] met the temperature target at lower velocity than air, but required increasing pumping energy at higher charging rates because oil transfers heat better than air while moving it demands more pumping power.

Direct immersion and dielectric-liquid cooling

In immersion cooling, cells or modules are in direct contact with an electrically insulating dielectric fluid, which can remove heat from a larger fraction of the cell surface than an indirect cold plate and potentially reduces interfacial thermal resistance. Depending on the design, the fluid may circulate through the enclosure or be sprayed over the cells. Fluid electrical resistivity, thermal conductivity, heat capacity, viscosity, boiling behaviour, chemical compatibility, material ageing, environmental impact, sealing, servicing and cost must all be assessed.

Phase-change material cooling

PCMs absorb heat as latent heat during melting and release it on solidification, buffering short-term temperature peaks without continuous pumping, and can be integrated around cells or modules and combined with fins, heat pipes or liquid cooling. Many PCMs, however, have low thermal conductivity and finite storage capacity; without a path to reject stored heat and regenerate the PCM, performance deteriorates under repeated high loads. This was seen in a PCM–TEC study [13], where PCM alone let the mean battery temperature reach an unsafe 85 °C because the PCM saturates once melted and the temperature keeps rising. Conductive additives, metal matrices or hybrid liquid–PCM arrangements may address some limitations at the price of added complexity.

Heat pipes

Heat pipes transfer heat by evaporation and condensation of a working fluid in a sealed structure, spreading heat from localised hot regions to a larger heat-rejection surface with no mechanical pump in the pipe itself. Integration is constrained by orientation, packaging, contact resistance and the capacity of the external heat sink.

Thermoelectric (Peltier) cooling

A thermoelectric cooler contains p-type and n-type semiconductor elements connected electrically in series and arranged thermally in parallel between ceramic plates. When direct current flows, charge carriers transport heat from one face to the other: the cold face is placed in thermal contact with the battery or a cold plate, while the hot face is connected to a heat sink, liquid heat exchanger or forced-air arrangement (Figure 2). Reversing the current polarity reverses the direction of heat flow, so the same module can also heat the pack in cold weather [11]. TEC systems provide precise, localised, refrigerant-free control with no moving parts in the module, although their COP is lower than that of vapour-compression systems [6].

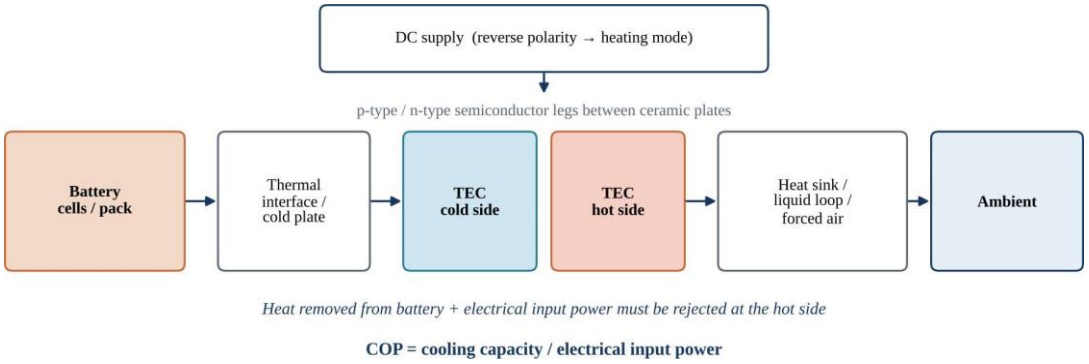


Figure 2. Heat-flow path in a thermoelectric battery-cooling arrangement. The hot side must reject both the heat removed from the battery and the electrical input power.

Cooling capacity depends on module current, temperature difference, thermal contact resistance and hot-side temperature. Increasing current may raise heat pumping over part of the operating range but also increases electrical consumption and Joule heating, so a module cannot be selected on its maximum temperature difference alone. A useful system-level definition is

$$\text{COP} = \text{cooling capacity} / \text{electrical input power} \qquad (2)$$

and for a complete EV configuration the denominator should include the TEC module and relevant auxiliaries such as pumps and fans.

Hybrid cooling

Hybrid BTMS combine two or more techniques, such as liquid cooling with PCM, air cooling with heat pipes, thermoelectric modules with PCM, or battery cooling integrated with a vehicle heat pump. A hybrid can use one method to control average temperature and another to reduce local hot spots or transient peaks, and may also support cabin heating or cooling, but additional components raise design complexity, control requirements, cost and possible failure modes. In the PCM–TEC study [13], adding a thermoelectric module lowered the mean battery temperature from 85 °C to 76 °C, circular fins lowered it to 65 °C and axial fins to 48 °C (Figure 3b), because the TEC removes extra heat and fins add heat-transfer area. In a PCM-in-water system with TEC cooling [14], battery temperatures fell by about 12% (50 W), 9% (30 W) and 14% (10 W) compared with natural convection.

Comparative Assessment

Table 1. Qualitative comparison of major EV battery cooling approaches.

Cooling method	Key strengths	Main limitations	Typical suitability
Air cooling	Simple, low cost, low mass, easy maintenance	Limited heat-transfer capability; flow maldistribution; fan power at high flow	Low-to-moderate heat loads
Indirect liquid cooling	High heat-removal capability; good temperature control	Pump power, pressure drop, leakage and added components	High-power packs and fast-charge duty
Immersion / spray cooling	Direct cell contact; potentially strong heat transfer and uniformity	Dielectric-fluid cost, compatibility, sealing and servicing	High heat flux and demanding thermal duty

PCM cooling	Passive heat buffering; no continuous pumping for latent storage	Low conductivity; finite storage capacity; regeneration required	Transient peak buffering and hybrid systems
Heat pipes	Passive heat spreading; compact heat transport	Integration and heat-sink constraints; orientation sensitivity	Localised heat spreading
Thermoelectric cooling	Precise, localised, refrigerant-free, reversible (heating/cooling)	Low COP; electrical input; hot-side heat rejection; pack-level scalability	Zonal or targeted control; hybrid use
Hybrid systems	Combine complementary strengths and improve uniformity	Higher cost, complexity and control burden	Applications with multiple thermal constraints

Performance indicators

The maximum cell temperature (T_{max}) indicates the hottest operating point in the pack, and the temperature difference (ΔT) between the hottest and coldest cells measures thermal uniformity; both should be reported together because a system can achieve a low T max while still producing a large cell-to-cell difference. Other important indicators include coolant pressure drop, pump or fan power, thermal response time, system mass, volume, cost, reliability, COP where relevant, and the energy needed to operate the BTMS. Comparisons between published studies must be interpreted carefully because results depend on cell chemistry and format, pack arrangement, C-rate, ambient and inlet temperature, flow rate, boundary conditions and whether the work is experimental or numerical.

Selected Findings from the Reviewed Cooling Studies

Tables 2 and 3 consolidate the quantitative findings of the cooling studies. Values are study-specific observations and are not normalised across studies. Figure 3 and Figure 4 plot representative reported values.

Table 2. Pack-level cooling studies (dielectric, cold-plate, spray and air-cooled packs).

System / study configuration	Test or model condition	Reported finding	Interpretation
[23] 52-cell NMC 21700 pack; MIVOLT DFK dielectric liquid; air, static-liquid and active-liquid cases	Ambient reported as 37 °C; air-flow and liquid-flow cases compared	Outlet condition: 0.5 m/s liquid case at 42 °C versus 5 m/s air case at 55 °C; air-cooled pack 48.8 °C without cooling and 42.8 °C with air cooling at 92% discharge	Indicates potential of liquid-based heat transfer; sensor locations and matched conditions must be checked in the source
[24] 48 V LFP 16S1P pack; COMSOL 6.2 pseudo-3D model; DF7 dielectric fluid	4C, 6C and 8C discharge cases	At 8C, maximum temperature decreased from 330.71 K to 306.41 K	Substantial simulated reduction at high rate; baseline definition requires verification
[25] Spray dielectric liquid cooling (SDLC); 9S7P Samsung INR18650-25R pack, 63 cells	Several dielectric fluids evaluated; Novec-7200 pressure drop at 4 L/min	Lowest maximum temperature ≈32 °C; Novec-7200 pressure drop 42.1 kPa at 4 L/min	Fluid selection trades thermal performance against hydraulic resistance
[26] Liquid-cooled BTMS designs I–VII; ANSYS Fluent 2023 R2; single-phase HTF	Inlet 298 K; 0.008 kg/s; 1C and 3C; VIKOR multi-criteria assessment at 3C	Design VII best thermally at 3C: T max 304.25 K, ΔT 3.16 K. Design VI ranked best by VIKOR: 0.3 kg, ΔP 150.5 Pa, ΔT 4.3 K, T max 305.6 K	The thermally best design is not necessarily the best overall when mass and pressure drop are included
[27] Air-cooled 5S5P 18650 pack; ANSYS Fluent R21	0.5C–3C; inlet velocities 5–13 m/s; natural circular inlet baseline	Natural-inlet T max 32.2, 45.3, 81.1 and 126 °C at 0.5C, 1C, 2C and 3C	Strong rise at high C-rate shows the limits of passive airflow

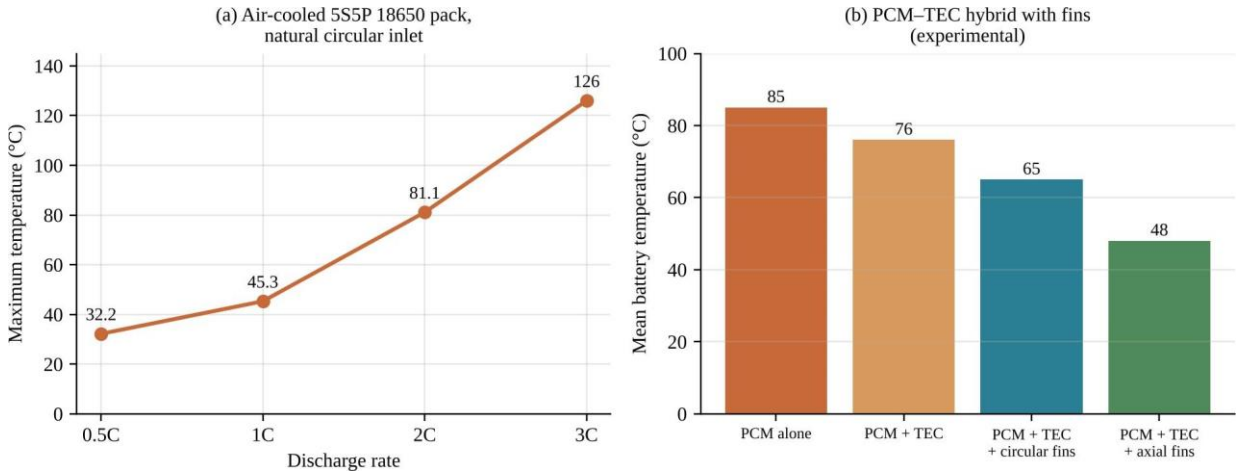


Figure 3. Representative reported temperatures: (a) maximum temperature of a natural-inlet air-cooled 5S5P 18650 pack versus discharge rate [27]; (b) mean battery temperature in the PCM–TEC–fin experiment [13].

Table 3. Thermoelectric, air-cooled, oil-cooled and PCM–TEC hybrid studies.

Study	Method	Key reported findings	Reason / mechanism
[6] Attar – zonal air-to-liquid TEC system for EVs	Design optimisation + prototype	≈1000 W cooling; experimental COP 1.09 (predicted 0.9); cold-air outlet ≈19.9 °C; COP below vapour-compression	Current creates a temperature difference; heat is absorbed at the cold side and rejected by exchanger and heat sink
[7] Nandakishora et al. – Peltier-hybrid cooling for EV batteries	Numerical simulation	At 1C, air needed ≈47.5 m/s for 313 K; oil met target at lower velocity but needed rising pumping energy; TEC hybrid improved regulation with a large energy penalty	Higher C-rate means more heat; oil transfers heat better than air but costs pumping power
[8] Wankhede, Pingale and Kale – air-cooled pack, Formula Student EV	CFD + experiment	Best case ≈17 m/s inlet air, battery 40–50 °C; simulation vs experiment ≈4.256%	Higher velocity sends more air over the cells, improving convection
[10] Lyu et al. – EV BTMS with thermoelectric cooling (Energy Reports 5, 822–827, 2019)	Experimental: TEC + liquid + forced air, single cell	Surface temperature fell ≈43 °C (55 °C to 12 °C) at reasonable power dissipation	Liquid carries heat to the TEC; forced air removes it from the hot side
[11] Lyu et al. – TEC for a new pack design in a copper holder (Results in Eng. 10, 2021)	Experimental: TEC at 30, 40, 50 V	40 V: ≈20 °C cooler than liquid cooling alone; 30 V: below 30 °C for 5000 s; 50 V (extreme): under 60 °C at 3000 s	Copper conducts well; reversing polarity also allows heating in cold weather
[12] Li et al. – TEC for a Li-ion module (Int. J. Photoenergy 2019)	Experimental: TEG + forced vs natural convection	TEG cooling best of three options: 16.44% reduction at 3C, with less energy than the two other TEG-based systems	Natural convection alone cannot remove high-rate heat; forced convection clears the hot side
[13] Alghamdi et al. – PCM + TEC to control thermal runaway (Case Stud. Therm. Eng. 52, 2023)	Experimental: PCM + TEC + fins	PCM alone 85 °C (unsafe); + TEC 76 °C; circular fins 65 °C; axial fins 48 °C	PCM saturates once melted; TEC removes extra heat and fins add area
[14] Alghassab – TEC modules with PCM (J. King Saud Univ. – Sci. 36(11), 2024)	Experimental: PCM-in-water with TEC at 50, 30, 10 W	Temperatures fell ≈12% (50 W), 9% (30 W), 14% (10 W) vs natural convection	PCM smooths fluctuations; water carries heat away; TEC cools the water

Note: [6] concerns a zonal air-to-liquid TEC system (cold-air outlet) rather than a battery pack and is included as evidence of TEC capacity and COP. Study [12] is labelled TEG-based in the source table while its title refers to a thermoelectric cooler; the label should be verified against the paper.

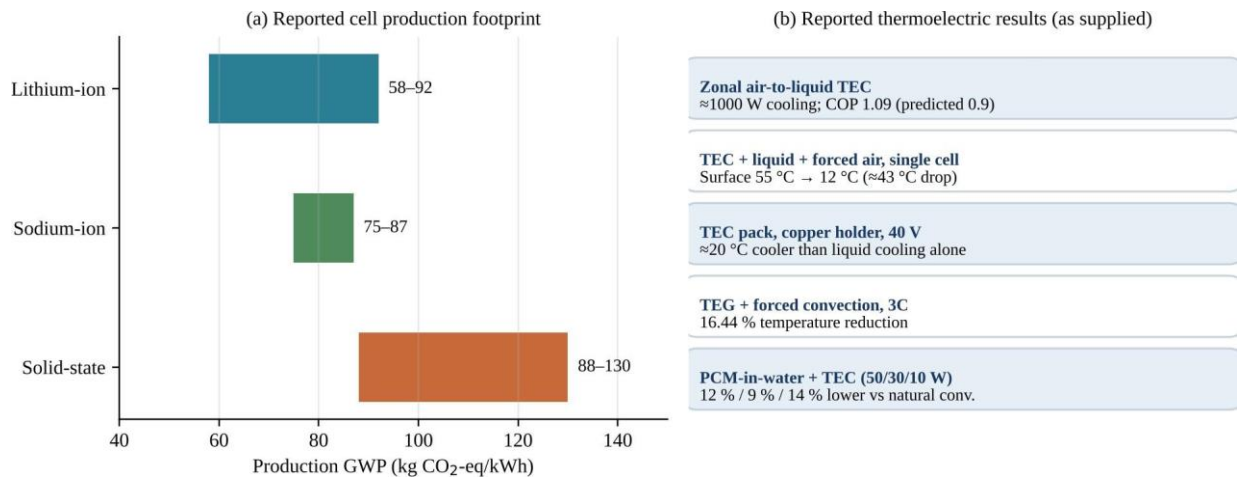


Figure 4. (a) Reported production footprints of lithium-ion, sodium-ion and solid-state cells [4]; (b) summary of reported thermoelectric results as supplied [6], [10]–[12], [14]. Values are study-specific and not directly comparable.

Intelligent Thermal Management, Charging Control and Preheating

Data-driven thermal management

Machine-learning models can estimate battery temperature from operating variables and historical measurements. An ensemble-learning study using real-world BMW i3 battery data combined six machine-learning models by weighted averaging and stacking, and reported very high temperature-prediction accuracy for the stacking model (RZ = 0.9999; RMSE = 0.0111) [5]. Such models can support predictive control, early detection of abnormal thermal behaviour and optimisation of cooling demand, but reliability depends on representative training data, sensor quality, validation across operating conditions and the ability to handle ageing and changing environments. A recent review likewise identifies AI/ML as a tool for temperature prediction and control alongside liquid, PCM and hybrid cooling [1].

Model-predictive control for fast charging and powertrain thermal management

Hu et al. combine a battery and thermal-management model with model predictive control (MPC), using an adaptive weighting strategy to balance charging time against thermal-management energy under state-of-charge, power and temperature constraints and charging-station availability uncertainty; the case study reports a 12.3% reduction in estimated charging time with negligibly higher BTMS energy use [18]. Xu et al. apply energy-efficient MPC to powertrain thermal management using a lumped-parameter thermal network and co-simulation (GT-SUITE, Motor-CAD, MATLAB/Simulink, CasADi); compared with rule-based control, battery energy consumption fell by 0.26% in an urban cycle and 1.06% in a highway cycle, with estimated inverter and motor lifetimes of 10,100 h and 20,100 h for a representative commute [20].

Rapid low-temperature preheating

Ye, Fu and Zhou studied rapid preheating of a 73 kWh, 770 V ternary lithium-ion pack using an independent water-circulation circuit and a high-voltage heater, comparing DC fast charging and onboard-charger slow charging with BMS current monitoring. The reported preheating time was 2,000 s; during the charging tests average pack temperature stayed below 35 °C and the maximum pack temperature difference below 6 °C, and the revised control strategy addressed current fluctuations during preheating [21]. Thermoelectric polarity reversal [11] offers a complementary heating route.

Structural and Electrical Safety Considerations

Integrated cell-to-pack cooling and mechanical protection

Li, Lu, Shen and Leontini present a cell-to-pack design based on an origami sandwich structure, combining ANSYS Fluent 19.0 thermal-fluid simulation (NTGK battery model), Abaqus structural analysis and quasi-static punch-compression tests with water coolant and a 15 mm punch. Compared with flat cooling channels, origami channels reduced maximum temperature by more than 2.6 °C at 5C discharge and by over 20 °C under internal-short-circuit conditions, and increased peak crushing force and impact-energy absorption, although additional coolant pressure drop may result [22]. The study connects thermal performance with structural protection rather than optimising cooling in isolation.

Electrical components

Farooq et al. used a multi-physics digital-twin approach (COMSOL Multiphysics 6.3 with busbar prototypes, mechanical tests, a Hall-effect current sensor and contact-resistance measurements) and reported stable operation up to 200 A, with a voltage drop of 0.009–0.047 V and contact resistance of 12.4–18.7 µfi. Under a 500 A transient, localised heating reached 273 °C and deformation exceeded 1 mm, supporting thicker cross-sections, integrated cooling or laminated busbars [19]. Electrical interconnects are thus part of the thermal-safety problem, not only the cells.

Sustainability, Recycling and EV Deployment

Life-cycle assessment shows that battery sustainability must be considered across materials, manufacturing, energy use and end-of-life. Degen et al. used a cradle-to-gate LCA with 18 impact categories to compare lithium-ion, sodium-ion and solid-state cells and reported production footprints of about 58–92, 75–87 and 88–130 kg CO -eq/kWh respectively,
2
with LFP cells needing the least production energy and design and manufacturing improvements giving reductions of up
to 38% for LFP; cobalt, copper and NMP contributed significantly [4]. A scenario-based LCA by Busch et al. found that an EV scenario reduced primary energy use by 20%, material extraction by 34% and CO -equivalent emissions by 61%
2
versus an ICEV-only future, avoiding about 300–600 kg CO e per kWh of battery (more with higher recycling), while
2
increasing metal and critical-mineral extraction [9].
Mathiyalagan and Kandasamy combined a literature review, a ten-member Delphi panel and system-dynamics modelling to show that higher recycling rates increase recovered-material reuse, reduce dependence on newly mined resources and improve the profitability of a circular battery supply chain [15]. On the charging side, a variable-universe fuzzy PID controller for urban charging-discharging balancing kept control error within ±0.1 kW under the reported conditions [16], and photovoltaic and battery-storage integration at charging stations can improve power management and reduce distribution-network stress [17]. Studies of electric mobility and the Indian EV market emphasise charging infrastructure and the conditions required for adoption [2], [3]. These factors determine the thermal loads that packs experience and strengthen the case for cooling systems that are not only thermally effective but also resource-efficient and maintainable.

Table 4. Control, charging, safety and sustainability studies included in the review.

Study	Method / tools	Main reported result
[4] Degen et al. – battery chemistry LCA	Cradle-to-gate LCA; teardown, literature, factory data	Production GWP: LIB 58–92; SIB 75–87; SSB 88–130 kg -eq/kWh; LFP lowest production energy CO_2
[9] Busch et al. – EV carbon handprint	Scenario-based LCA	EV scenario: −20% primary energy, −34% material -eq vs ICEV-only extraction, −61% CO_2
[15] Mathiyalagan and Kandasamy – recycling economics	Literature review; Delphi panel; system dynamics	Higher recycling supports material recovery and circular-chain profitability
[16] Ding, Zheng and Chen – urban charging balance	Variable-universe fuzzy PID; Monte Carlo; Markov decision	Control error within ±0.1 kW
[17] Ray, Kasturi and Nayak – PV + storage charging stations	Power-system modelling and simulation	Improved power management and reduced grid stress (no numerical values supplied)
[5] Naresh and Ayyappa – ML thermal management	Heterogeneous ensemble learning (BMW i3 data)	Stacking model RZ = 0.9999; RMSE = 0.0111
[18] Hu et al. – fast charging with BTMS	Battery/thermal model; MPC; adaptive weighting	12.3% shorter estimated charging time with negligibly higher BTMS energy
[20] Xu et al. – powertrain thermal MPC	GT-SUITE; Motor-CAD; MATLAB/Simulink; CasADi/SQP	Battery energy use −0.26% urban, −1.06% highway vs rule-based control
[21] Ye, Fu and Zhou – low-temperature preheating	73 kWh pack; HV heater; liquid loop; BMS monitoring	2,000 s preheating; average <35 °C; maximum difference <6 °C
[19] Farooq et al. – electrical components	COMSOL 6.3; digital twin; busbar tests	Stable to 200 A; at 500 A transient, 273 °C local heating and >1 mm deformation
[22] Li et al. – origami cell-to-pack design	ANSYS Fluent 19.0/NTGK; Abaqus; 15 mm punch test	T_{max} reduction >2.6 °C at 5C and >20 °C under internal short circuit; improved crushing force

Comparative Discussion

Air cooling is attractive where heat generation is modest, simplicity matters and space allows airflow, but maximum temperature can rise sharply with C-rate (32.2 °C at 0.5C to 126 °C at 3C with a natural inlet [27]). Forced airflow improves performance (about 17 m/s kept a Formula Student pack within 40–50 °C [8]) at the cost of fan energy, and an air-only solution at 1C required about 47.5 m/s to meet a 313 K limit [7].

Liquid cooling provides a stronger heat-transfer pathway and suits compact, high-power packs. The cold-plate study [26] shows why optimisation should not rely on maximum temperature alone: Design VII was thermally strongest, whereas Design VI ranked highest under the VIKOR multi-criteria method because it balanced temperature with mass and pressure drop. Oil cooling offers similar benefits but with pumping-energy growth at higher charging rates [7]. **Direct dielectric and spray cooling** give close thermal contact; the reported ≈32 °C maximum temperature in the spray study [25] is promising, but the 42.1 kPa pressure drop of Novec-7200 at 4 L/min, fluid cost, ageing, compatibility and environmental aspects must be included in a complete assessment.

Thermoelectric cooling delivered the largest reported temperature reductions in the experimental studies (a 43 °C drop [10]; about 20 °C cooler than liquid cooling alone [11]) and uniquely allows both cooling and heating by reversing polarity [11]. Its limitation is energy: the experimental COP of 1.09 [6] is below that of vapour-compression systems, and a Peltier-hybrid simulation reported a large additional energy penalty [7]. TEC is most compelling where precise or localised control, absence of refrigerant or bidirectional thermal control is valued over efficiency, or where it is coupled with forced convection to reduce energy use [12]. It may be more suitable for zonal cooling than as the sole method for a large pack.

PCMs buffer short peaks and reduce local temperature variation, particularly when combined with a means of rejecting accumulated heat: PCM alone reached an unsafe 85 °C, while PCM with a TEC and axial fins held 48 °C [13], and a PCM-in-water TEC arrangement reduced temperatures by 9–14% [14]. **Hybrid systems** offer the best system-level flexibility, but added components and controls can increase cost, mass and failure modes. **Intelligent control** (ML prediction [5], MPC [18], [20], preheating [21]) improves use of the cooling hardware, provided it is backed by physical understanding, safety limits and validation on real vehicles.

A recurring theme is a performance–penalty trade-off: fan energy for air, pumping energy and pressure drop for liquid, oil and spray systems, electrical input and low COP for TEC, and saturation or heat-rejection needs for PCM. From a life-cycle perspective, cell production carries roughly 58–92 kg CO_2-eq/kWh [4], yet EV deployment still lowers CO_2-equivalent emissions by 61% versus an ICEV-only scenario [9]. Keeping batteries within their intended temperature window supports the long service life that spreads this burden over more kilometres, although the reviewed studies do not quantify that link directly. Numerical results from different studies cannot be ranked unless cell format, chemistry, ambient temperature, C-rate, heat generation, coolant inlet condition, flow rate and measurement definition are made comparable.

Research Gaps and Future Scope

- **Standardised comparison:** report cell chemistry, format, pack geometry, ambient temperature, C-rate, state of charge, coolant inlet temperature, flow rate and sensor positions, together with T_{max}, minimum temperature and ΔT.
- **Energy and hydraulic penalties:** include pump or fan power, pressure drop, TEC electrical input and COP, and net system energy; total COP should include pump and fan power.
- **Pack-level validation:** progress from single cells and small modules to representative modules and full packs under different C-rates, ambient temperatures, ageing states and fault scenarios; validate numerical models against experiments with uncertainty analysis.
- **Hybrid and zonal design:** investigate zonal thermoelectric cooling combined with liquid cold plates or PCM, optimise the hot-side heat exchanger together with the TEC module, and weigh the extra mass, cost and failure modes of hybrids.
- **Immersion and PCM materials:** study long-term dielectric-fluid compatibility, leakage, flammability, environmental impact and recycling; pursue PCM conductivity enhancement and regeneration strategies.
- **Control and AI/ML:** test models on independent datasets, chemistries and operating conditions; ensure explainability, sensor-fault tolerance and safe fallback control; develop adaptive control including TEC heating/cooling switching and grid-aware charging.
- **Vehicle integration and safety:** assess mass, volume, crashworthiness, vibration, serviceability, thermal-runaway propagation (including PCM saturation), busbar heating and post-crash behaviour.
- **Life-cycle and circularity:** state functional unit, energy mix and system boundary; include recovery yield, process energy and end-of-life treatment, and relate BTMS choices to battery-level LCA results.

Conclusion

Battery thermal management is essential for EV battery performance, safety, reliability and service life. The consolidated evidence shows that air cooling is simple and economical but becomes inadequate as heat generation and pack power increase; indirect liquid cooling offers strong heat removal and can be optimised by balancing peak temperature, uniformity, pressure drop and mass; direct dielectric immersion and spray cooling are promising for close-contact cooling but need careful fluid selection and reliability evaluation; thermoelectric cooling achieves large temperature reductions and supports both heating and cooling, but its lower COP and added energy demand must be weighed; and PCM and heat-pipe systems provide passive buffering or spreading, with PCM–TEC and other hybrids combining buffering and continuous heat rejection at the price of complexity.

No single method is optimal for every EV application. The preferred BTMS should be selected using representative duty cycles and a multi-objective assessment of thermal performance, parasitic energy, weight, cost, durability, safety and life-cycle impact. Combining validated coupled electrochemical–thermal–fluid models, well-designed cooling hardware, structural and electrical safety design, and intelligent monitoring and control offers a promising route towards safer and longer-lasting EV battery packs.

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