

Future development trends in new energy vehicle thermal management technology in the context of carbon neutrality and global hydrofluorocarbon regulations

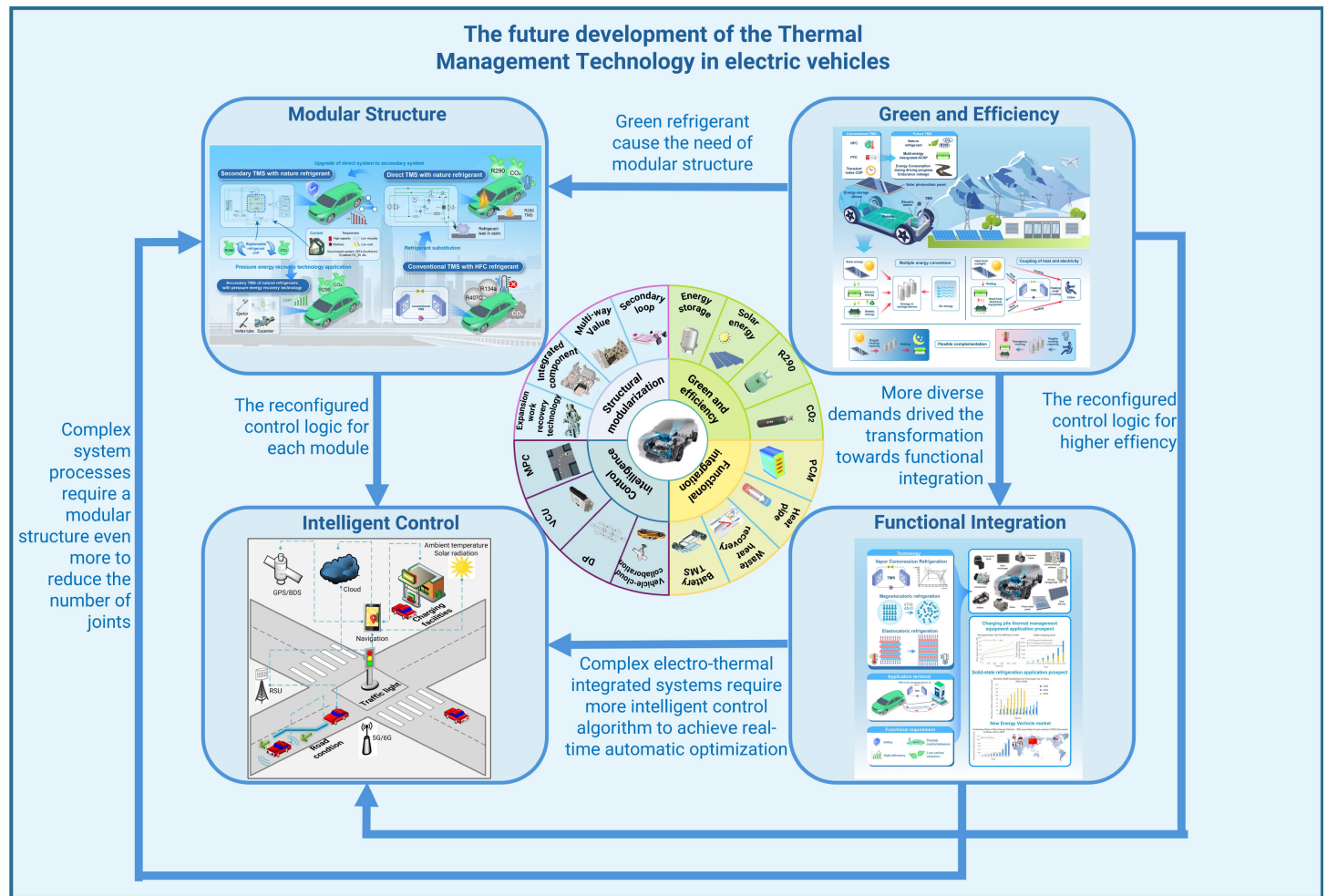
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- This study systematically explores the future of NEV TMS: green and efficiency, functional integration, modular structure, and intelligent control.
- Natural refrigerants, and thermal storage are identified as pivotal green technologies for performance optimization and carbon emission.
- Non-vapor compression, integrated temperature and humidity management, and interface with charging pile act as the future of system functions.
- Modular secondary-loop systems are the dominant approach to improving versatility and enabling pressure energy recovery.
- Intelligent thermal management solutions combined by vehicle-mounted thermal management energy hub with cloud information interaction are fatal parts of vehicle TMS.

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With the rapid development of the new energy vehicle (NEV) industry, thermal management technology has emerged as a critical area of research and development. Effective thermal management is essential for addressing key challenges such as winter driven-range anxiety, battery thermal safety, energy saving and F-gas emission reductions. In the context of evolving global energy structures, environmental issues, and refrigerant substitution regulations, the future development of NEV thermal management industry is progressing toward the "new four modernizations": green and efficiency, functional integration, modular structure, and intelligent control. This paper explores these four aspects in detail. First, continuous performance optimization and the adoption of green technologies remain central themes of thermal management with emerging solutions such as thermal storage and CO₂-based natural refrigerants expected to play a significant role. Second, more functional requirements, particular the integration of high-power on-board electronics are likely to be addressed through the non-vapor-compression refrigeration technologies. Third, the adoption of secondary-loop systems with modular structures will become the dominant approach to enhance the versatility, making pressure energy recovery technologies within thermodynamic cycle increasingly significant. Finally, the development of intelligent thermal management solutions such as model predictive control (MPC)-based energy hub framework will certainly become an indispensable part of vehicle thermal management system. Based on these considerations, this paper proposes two innovative evaluation factors and highlights the flexible applications of future NEV thermal management systems. The findings aim to provide valuable insights for scholars, practitioners, manufacturers and policymakers working toward the advancement of NEV thermal management technologies.

INTRODUCTION

As fossil energy becomes increasingly scarce and the greenhouse effect intensifies, energy conservation and emission reduction have emerged as global priorities for achieving a sustainable and low-carbon future. According to the International Energy Agency, the transport sector accounts for nearly 40% of total CO₂ emissions¹ and continues to grow at a high rate.² In response to the urgent climate challenge, the Intergovernmental Panel on Climate Change (IPCC) has emphasized the need to limit Global Warming to 1.5 °C to prevent irreversible impact of climate on ecosystems.³ To meet this goal global carbon neutrality must be achieved by 2050⁴—ten years ahead of China's official target. However, projections indicate that China's carbon emissions may not peak until 2036, six years later than its commitment under the Paris Agreement. A key factor in the delay is the transport sector which is reported of nearly 8.5 billion tons of CO₂ by 2020⁶² and is not expected to reach its peak until 2043.⁵ Given these challenges, transitioning the transportation and automotive industries toward cleaner energy sources is essential. Reforming the energy structure in these sectors represents a crucial strategy of advancing energy substitution and reducing carbon emission on a

global scale.

In the global transition toward sustainable transportation, new energy vehicle (NEV) technologies have been considered as a key strategy of international energy reform for reducing greenhouse gas emissions and other pollutants.^{6,181} Many countries and regions such as Europe,⁸ China,⁹ and Canada¹⁰ have recognized the critical role of NEVs in shaping an environmentally friendly industry,⁷ and have introduced phase out schedules for internal combustion engine vehicle (ICEV) sales between 2030 and 2050. As a result, the production and sales of NEVs have accelerated significantly in recent years. From a global perspective, electric vehicle (EV) sales have risen sharply, reaching 6.75 million in 2021, 14 million in 2023 with projections estimating over 228 million by 2030. Currently the total number of EVs on the roads has surpassed 40 million.^{11,172} Within the NEV market, aside from plug-in hybrid vehicles (PHV) that is more like a transitional alternative, battery electric vehicles (BEV) and fuel cell vehicles (FCV)¹² are the two dominant technologies while BEVs hold a substantial market share, accounting for more than 80%¹⁴ in the NEV market due to their rapid technological advancements and commercialization. Meanwhile, FCVs represent strong motivation and growth potential due to their superiority of endurance mileage and charging time.¹³

However, despite the rapid growth of EV technology, it still remains a relatively new field with several technical challenges that require further optimization. Key issues including range anxiety in cold winter,¹⁵ year-round cabin comfort,¹⁶ battery safety,¹⁷ and the stability of electronic components as the power density increases.¹⁸ Notably many of these challenges are closely related to the vehicle's thermal management system. Unlike ICEV, EVs demand more precise, sophisticated and integrated thermal management solutions. As a result, thermal management has emerged as a critical research focus alongside advancements in power and battery technologies.¹⁹⁻²⁰

The thermal management system (TMS) in EVs typically consists of several key components, including the cabin air conditioning & heat pump (ACHP), the battery thermal management module (BTMM), and the electronic units thermal management module (ETMM), etc.^{21,184} These systems play crucial roles in enhancing energy efficiency and reducing emissions. Giving the multifunctional and multi-purpose requirements in EVs, TMS is not only extremely important to the EV's high-efficient operation, but also plays a significant role in maintaining safety, comfort and system stability by regulating temperatures under various operating conditions.²²

As a rapidly growing pillar industry, the EV market is expected to expand significantly with ongoing technological advancements and decreasing costs. Projections indicate that the market will surpass the trillion level (in RMB) by 2030.^{23,24} Likewise, as a crucial component of EVs, the EV's TMS market is anticipated to exceed 100 billion RMB in the next decade, drawing considerable attention from the academic and industrial communities. Given its growing importance, it is essential to systematically outline the future development trajectory of TMS technology, focusing on addressing key challenges

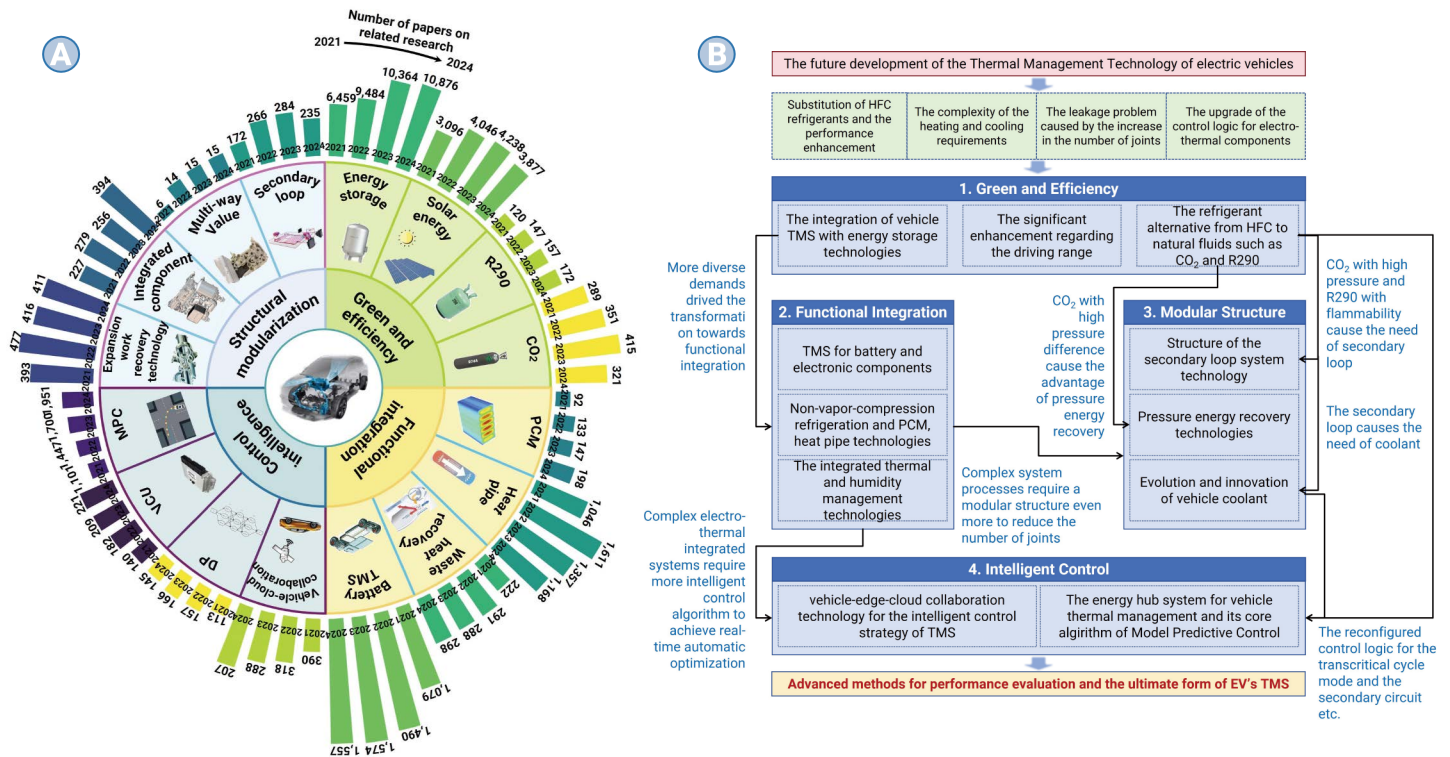


Figure 1. (A) Research and development trend of thermal management technology for new energy vehicles. (B) Research idea diagram of the core relationship between the "new four modernizations".

while streamlining less critical aspects. This approach will facilitate the rapid and efficient industrial application of TMS, further supporting the widespread adoption of EVs.

This study defines the future development of TMS in EVs as "new four modernizations", encompassing green and efficiency, functional integration, modular structure, and intelligent control. "Green and efficiency" emphasize the adoption of natural refrigerants to reduce greenhouse gas emissions, supplemented by multi-energy comprehensive utilization technologies such as thermal storage and solar energy to enhance energy utilization efficiency. "Functional integration" involves coupling all thermal demands including those for cabin, battery, motor,¹⁸⁵ electronics,¹⁸⁶ etc. within a unified thermodynamic cycle. When necessary, flexible thermal transport equipment such as heat pipe can be incorporated. "Modular structure" focuses on integrating multiple components into a cohesive design to minimize issues like leakage and other safety problems associated with excessive pipe joints. "Intelligent control" leverages advanced optimization algorithms to manage increasingly complex TMS, ensuring lower energy consumption and improved efficiency across the full operational cycle. As shown in Figure 1A, these four aspects have gained growing attention in the academic community. Over the past four years, research publications on related sub-fields have shown a consistent upward trend. Based on this, this paper will further explore the future development prospects of these key areas. Additionally, a research idea diagram of the core relationship between the "new four modernizations" is shown in Figure 1B.

CONTINUOUS PERFORMANCE IMPROVEMENT AND GREEN TECHNOLOGY: KEY TRENDS IN THERMAL MANAGEMENT TECHNOLOGY

Substitution of refrigerants

Vapor compression refrigeration (VCR) is currently the most established and widely adopted technology across commercial, industrial, and residential applications, and it is the most widely promoted technology in TMS of EVs. Over the course of nearly two centuries, the refrigerants used in VCR systems have undergone multiple rounds of replacement, driven by the growing concerns about safety (toxicity and combustion) and environmental protection (such as ozone hole²⁶). Currently, HFC (hydrofluorocarbon) refrigerants including R134a in automobiles^{26,27} and R407C in bus and rail vehicles^{28,29} are

the most commonly used options in TMS.

However, HFC refrigerants are far from ideal working fluids in TMS, particularly in terms of energy saving and environmental protection.³⁰ Specifically, the absence of engine waste heat in NEVs has led to the introduction of alternative heating approaches during winter.³¹ Under typical winter conditions, the performance of HFC refrigerants deteriorates sharply, necessitating the use of PTC heater (positive temperature coefficient, an electric heating materials supplementary or primary heating device.^{32,33} Given the low energy efficiency of PTC heater compared to heat pump, this results in concerns over NEV vehicle range and energy consumption, contributing to mileage anxiety.^{34,35}

On the other hand, the exceptionally high 100-year-GWP (Global Warming Potential) of R134a and R407C (1430 and 1774, respectively^{36,37}), has led to their classification as potent greenhouse gases under the Kyoto Protocol.³⁸ Additionally, the Montreal protocol amendments to Kigali³⁹ have designated 18 kinds of HFCs as controlled substances worldwide.

As a result, there is a broad consensus in industry and academia that the transition from HFCs to natural refrigerants is an urgent need. Considering the restriction from PFAS laws, the use of HFO substitutes (such as R1234yf) faces new challenges.⁴⁰ Thus, the primary alternatives focus on the two options: carbon dioxide (CO₂) and propane (R290).

Due its pollution-free nature, environmentally friendliness, cost-effectiveness, and excellent heating performance,^{41,42} CO₂ has become an almost ideal solution in vehicle TMS, space heating, hot water supply, drying industry, commercial cold chain, ice and snow sports and other integrated cold/hot supply fields.⁴³ From an environmental perspective, CO₂ is a natural working fluid with GWP of and ODP (Ozone Destroying Potential) of 0. It is generally derived from industrial by-products and does not bring additional pollution to the atmosphere during its use and discharge. In terms of energy saving, the transcritical CO₂ heat pump could operate stably at ambient temperatures as low as 30 °C with a relatively high COP (Coefficient of Performance, over 2.0),^{44,45} which make them an effective substitute for the PTC heater for significant energy savings.

In contrary, CO₂ TMS typically operates in a transcritical cycle, which differs from the conventional subcritical cycle.⁵³ That is, all the components of the vehicle TMS have to be redesigned if CO₂ is adopted to replace

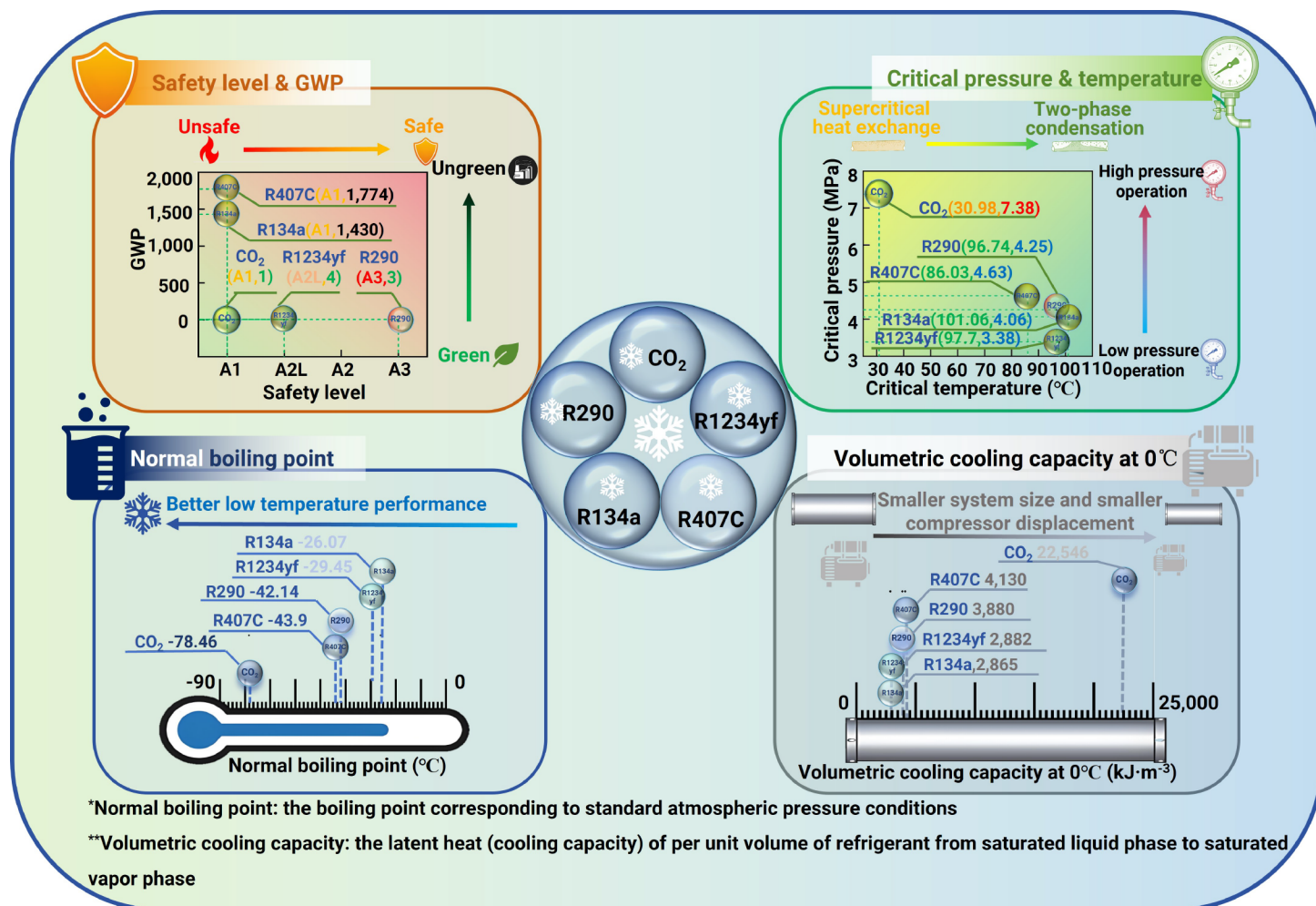


Figure 2. Comprehensive evaluation of R134a, R407C, and their main alternatives.^{36-37,167-168}

R134a/R407C. From a market perspective, this systematic disruption and reconstruction present both challenges and opportunities for researchers, practitioners, manufacturers, and policymakers.

Similarly, R290, a hydrocarbon with a very low GWP and an ODP of 0 can be extracted directly from liquefied petroleum gas. R290-based vehicle TMS has showed strong performance under operating conditions of 55°C for cooling and -20°C for heating,⁴⁶ positioning it as another ideal alternative to R134a. However, studies have also pointed out that, the extraction of R290, involves the release of toxic gases (such as CO, SO₂, and NO₂) during the petroleum refining process.⁴⁷ Besides, R290 is a flammable and explosive substance,⁴⁸ which poses a constraint limiting its rapid development especially in EVs, where frequent electrical sparks are a concern. Therefore, the secondary loop technique must be adopted in R290-based TMS, preventing the refrigerant leakage into the passenger cabin.⁴⁹

R1234yf (ODP=0 and GWP=4¹⁶⁷) was once considered as the leading alternative to R134a due to its thermodynamic properties.⁵⁰ Although it does not require system redesign to replace R134a in TMS using R1234yf, its heating performance at low-temperatures is sub-optimal, which needs to be supplemented by a PTC heater. In addition, as a fluoride compound, most of the raw materials, including R1234yf itself, are included in the restricted list of the EU PFAS Act. Furthermore, studies reported that R1234yf can degrade into harmful substances such as TFA (trifluoroacetic acid⁵¹ or HFC-23 (trifluoromethane with GWP=14800)^{52,167} in the natural environment, which could cause certain environmental risks. Moreover, R1234yf is slightly combustible, which introduces certain safety concerns during its use in NEVs.

In summary, a comprehensive evaluation of R134a, R407C, and their primary alternatives is shown in Figure 2. All data were collected from literature or derived from Refprop 9.0 database (NIST Standard Reference Database 23, Version 9.0).¹⁶⁸ Under the promotion of the PFAS proposal, tran-

sitioning the working medium of EV TMS from fluoride to natural fluids has become imperative. Among these CO₂ and R290 are the most promising options due to the favorable characteristics of safety (via secondary loop systems⁴⁹), environmental sustainability, and wide temperature range compatibility, etc.

Performance improvement toward enhancing driving range and reducing carbon emissions

Typically, VCR adopts the heating/cooling COP (defined as the ratio of system heating/cooling capacity to total power consumption) as a standardized performance index. However, in the local micro-energy network of EV applications with a single energy supply (battery) and multi-energy consumption, the instantaneous COP does not fully reflect the efficiency improvements of other components resulting from the TMS temperature regulation in NEVs.¹⁸⁷ For example, maintaining the battery operating within a right temperature zone reduces internal resistance of the battery and improves the efficiency. Thus, the energy consumption associated with the battery temperature management may be partially or entirely offset by these efficiency gains.

On the other hand, it is well known that the driving range of NEVs is highly affected by factors such as climate, driving conditions, and components' energy efficiencies.⁵⁴ Therefore, a comprehensive exploration of the impact of TMS performance optimization on vehicle range is crucial for advancing the development of NEVs and the related industries.^{55,56} In other words, regardless of the refrigerant used or the operating conditions chosen, the ability to efficiently allocate energy through TMS to maximize vehicle mileage while ensuring operation safety, stability, and comfort, will become the primary metric for measuring the TMS performance in the future.⁵⁶ Considering the thermal-electric coupling interactions between various components in the EV

local energy network, achieving the maximum driving range relies on the implementation of complex advanced control algorithms and novel control structures, which will be described in section 5 of this study. In addition to the control algorithms, this section will also explore thermodynamic-related technical solutions that may be helpful in the future.

Under typical driving conditions, the cooling/heating requirements (cabin, battery, motor cooling, etc. included) are the second greatest demand on battery energy following the power system. This impact largely affects the NEV driving range particularly in cold climates⁵⁶ due to its higher internal resistance under low temperatures. For instance, thanks to its 2-5 times the energy efficiency of PTC (which operates at only 92%~95%⁵⁸), the heat pump technology, especially transcritical CO₂ heat pump technology is increasingly recognized as an essential solution for improving NEV's TMS, particularly under ambient conditions down to -30°C.⁵⁷

From the future development perspective optimizing CO₂ TMS is divided into two aspects: instantaneous performance improvement and full driving-range performance improvement. Much of the current research on CO₂ TMS used in EVs focuses on the enhancement of the instantaneous COP, which includes discharge pressure optimization and control,⁵⁹ throttling loss recovery,⁶⁰ battery evaporative cooling,⁶¹ etc. By improving performance across these areas, the CO₂ TMS can reduce the battery energy needs while maintaining the same cooling/heating capacity, thereby largely extending the NEV driving range. However, COP is an instantaneous measure, whereas driving range is an integral global concept, and there is no strict correspondence between these two under certain conditions.⁵⁶ For instance, applying an optimal discharge pressure control strategy aimed to pursue the real-time maximization of COP in winter may lead to lower the evaporating pressure, resulting in frost formation on outdoor heat exchanger, which would sharply reduce heating performance once the frost reached a certain thickness. Therefore, when considering the whole driving range, this approach may not be scientifically sound.

To address such challenges, researchers have paid more attention to the full-range performance optimization method. Taking the frost problem as the example, based on the in-depth analysis of the impact of frost on driving range under various operating conditions, a novel concept called the frost-free control method for TMS operating pressure has been proposed.⁵⁶ This method has the potential to increase driving range by up to 10%. In fundamental terms, the frost-free control method is actually an energy transfer technique in the time domain. Both the optimal discharge pressure control and the optimal COP target are discarded under frost-prone conditions. This trade-off involves sacrificing part of the heating capacity to ensure a higher evaporation temperature above the dew point temperature of the outdoor ambient. As a result, frost formation is prevented, and while system performance does not reach its instantaneous peak, it remains stable and does not deteriorate remarkably throughout the entire driving range.⁵⁶

Referring to the overall time domain performance optimization principles, researchers should consider the maximum driving range as the only evaluation index for the future development and ongoing optimization of the NEV TMS. This approach represents an important exploration in the emerging cross-cutting industry.

Meanwhile, as a significant manifestation of the green technology route, carbon emission should be considered as another critical evaluation index. Although EVs do not directly produce carbon emissions in practice, there are instances where indirect emission occurs. For instance, according to the current coverage rate of new energy power generation, EVs inevitably contribute to the load of thermal power plants, which is one of the most important indirect carbon emissions.⁶³ Studies have explored TMS-related carbon emissions through various approaches, such as distributed charging pricing strategy,⁶⁴ carbon trading economics in EV distribution system,⁶⁵ and reducing the carbon footprint of battery life cycle through improved thermal management.⁶⁶ Notably, improvements in driving range and reductions in vehicle power consumption are closely interconnected. Therefore, prioritizing driving range optimization is the best choice from the perspective of carbon emissions. In addition, a detailed evaluate method of vehicle TMS in terms of carbon emissions is also proposed in this paper, which is outlined in Section: Equivalent carbon emission factor of the TMS.

Integration of vehicle TMS with energy storage technologies

As the electrification of the transportation industry progresses, the vehicle is transitioning from traditional internal combustion engine modes to electrically driven and fuel cell-driven modes. This transportation is fostering the integration of the vehicle industry with other energy sectors, especially energy storage technologies.⁶⁷ This combination is generally manifested in two ways: on the micro level, heat/cold storage modules can be used as an important part of the vehicle TMS to cope with the instantaneous high-power cooling or heating needs;⁶⁸ on the macro level, EVs themselves, which can be treated as a huge electric storage equipment, become an important link between the new energy network and flexible matching systems.⁶⁹ Given the primary focus of this paper is the EV's TMS, the micro-level perspective is emphasized here. For instance, with the development of fast charging technology, vehicle charging time can be greatly reduced. However, heat accompanied by fast charging is gradually approaching the upper limit of the TMS cooling capacity. To mitigate this, the vehicle TMS can be integrated with cold storage equipment, allowing the cooling capacity to be stored in advance. In addition, future vehicle TMS solution will inevitably be combined with solar energy and waste heat recovery technology. However, a potential challenge arises from the mismatch between availability of solar energy or waste heat and the heat temporal demand for heat for which thermal storage system will prove essential.

Compared with conventional ACHP and battery heat dissipation systems, the introduction of energy storage module in EVs leads to an increase in electro-thermal and thermo-thermal conversion phenomena.^{73,74} However, there are limited in-depth discussions on the inevitable electro-thermal conversion processes involved.⁶⁹ These energy transfer processes are inherently accompanied by energy dissipation, which is ultimately reflected in the form of thermal energy. This dissipation may cause serious risks such as thermal runaway and safety concerns (such as the heat generated during fast charging). Therefore, the TMS in NEVs would also be responsible for efficiently reusing the thermal energy. This capability will increase the demand-side management capability for users, enabling better control over energy consumption and thermal risks.^{71,72} Additionally, even in some studies, scholars have achieved improvements in the energy efficiency of thermal management systems by recovering exhaust gas heat.²¹⁶

In summary, as a terminal carrier of a complex energy system, EVs involve various forms of electric-thermal coordination and energy conversion processes. Furthermore, EV create comprehensive demands for cold, heat, and electricity, such as cabin cooling/heating, battery cooling/preheating, motor /electronics active cooling, power demand, auxiliary unit demands, etc. This complexity presents challenges related to the adaptation and new regulation of heterogeneous energy flows across both spatial and temporal scales.²¹⁸ Therefore, in addition to the battery that could be used as the electric energy storage device, thermal energy storage devices (such as phase change materials⁷⁰) are also promising for waste heat recovery,²¹⁹ braking energy recovery, coupling with solar energy (solar thermal or photovoltaic), etc.⁷⁵ The schematic diagram of vehicle TMS with natural refrigerants and an energy storage module is shown in Figure 3, which illustrates the achievement of multiple energy conversions, the coupling of thermal and electrical systems, and flexible complement. It is worth noting that although the integration of energy storage and multi-energy complementation technologies in TMS can significantly enhance system efficiency, it will inevitably lead to an increase in costs and system complexity, and also occupy vehicle installation space. Under the current industrialization conditions, the economic viability and vehicle adaptability are relatively low. However, with the maturation of technology and the improvement of the industrial chain, the initial investment cost reduction is inevitable, and there is no technical difficulty for vehicle manufacturers to allocate installation space for those components. Therefore, the development of these technologies is not restricted.

Research has also been conducted on the efficiency and carbon emissions of TMSs using the aforementioned refrigerants in NEVs. In terms of refrigerant system architecture, due to flammability restrictions, R290 requires a secondary cycle system, while CO₂, R134a, and R407C still use a direct system architecture. Additionally, the TMS in NEVs integrates thermal management requirements for the cabin, battery, motor, and other components, and incorporates heat recovery—an effective method to enhance the

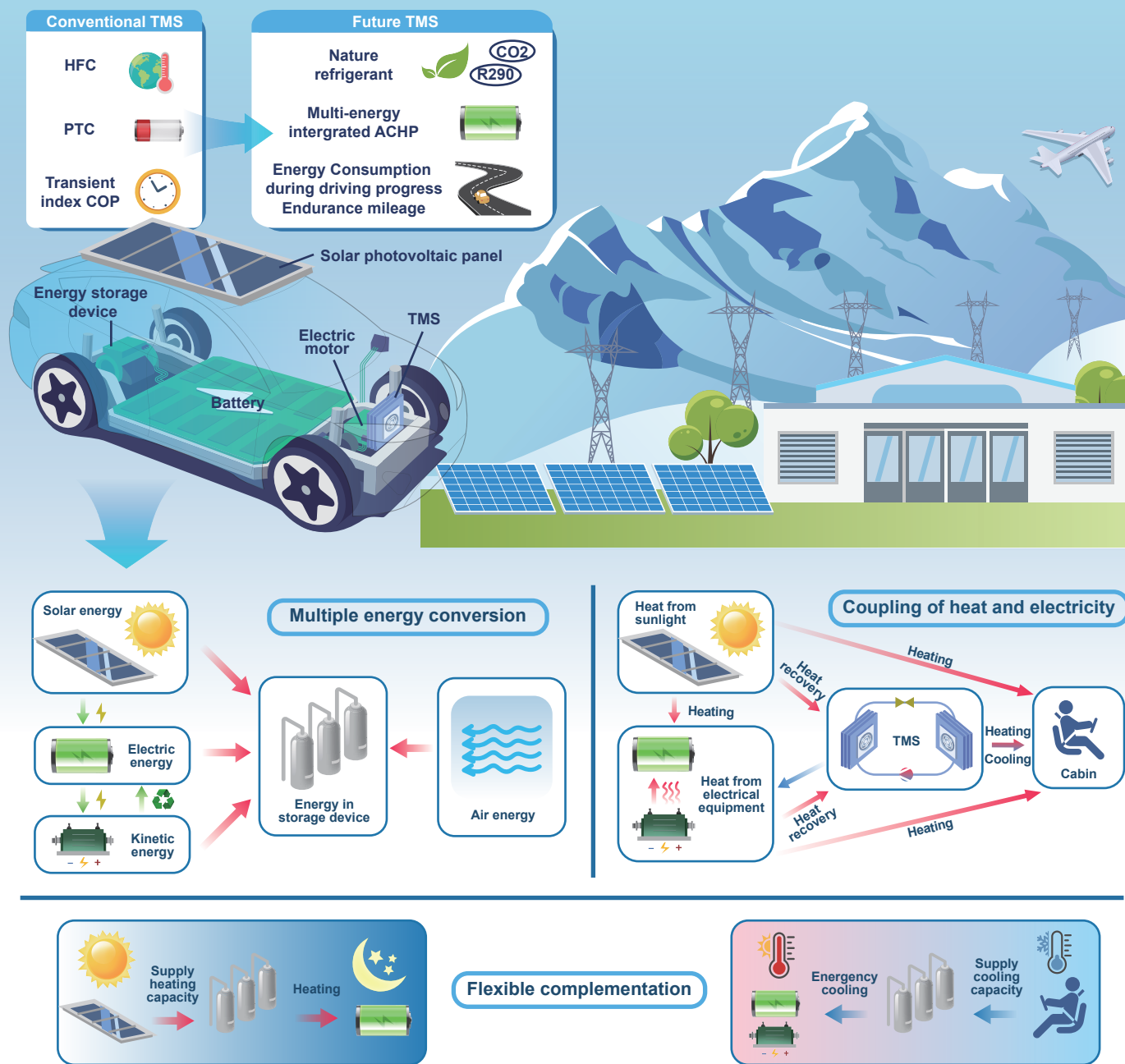


Figure 3. The integration of thermal management, solar energy, and energy storage in EVs

heating performance of the TMS in low-temperature environments—into the system. For R134a (passenger vehicles)/R407C (buses and high-speed trains), CO_2 and R290, reasonable architecture and accurate vehicle models were constructed. Subsequently, we conducted multi-mode steady-state performance calculations across the entire temperature range and dynamic simulations under CLTC/CHTC cycles. Finally, by combining climate data, the performance characteristics of each refrigerant in terms of energy efficiency and carbon emissions across different regions were obtained, as shown in Table S1 & S2.

According to the data, in cooling mode, the COP of the CO_2 TMS lags behind R134a TMS by approximately 25% due to the limitation of release temperature of gas cooler, while the gap between R290 and R134a is smaller because R290 has high latent heat of vaporization despite larger temperature difference. Conversely, in heating conditions, CO_2 demonstrates a significant advantage, capable of providing sufficient heat at -30°C without relying on a PTC heater. However, R134a TMS faces operational limitations in cold climates due to high pressure ratios or low-pressure side pressures

approaching atmospheric pressure (attributed to thermodynamic characteristics such as the standard boiling point), which restricts their effective deployment. This forces the system to rely on PTC heaters to provide heat to vehicle components, significantly increasing energy consumption. By adopting a waste heat recovery architecture, heat can be absorbed from higher temperature coolant by a water gas cooler to improve evaporating temperature. Therefore, the COP of R134a TMS and R290 TMS can be effectively improved by over 20%, as these refrigerants have a large heat transfer temperature difference and a low evaporation temperature. In terms of carbon emissions, alternative refrigerants R290 and CO_2 can effectively reduce TMS's direct carbon emissions by approximately 1500 kg CO_2 eq. However, indirect equivalent carbon emissions are influenced by local climate conditions and are also related to energy efficiency performance, with R290 and CO_2 suitable for different regions.

We previously studied the thermodynamic performance and carbon emissions analysis of replacing R407C with CO_2 in new energy high-speed railways and buses. The results indicate that the CO_2 system significantly

outperforms R407C in heating performance, but cooling performance still requires improvement.¹⁹⁷ In cooling mode, the CO₂-Advanced system equipped with an expander achieves a maximum COP improvement of 13.59% compared to the R407C system.¹⁹⁸ From the energy and environmental perspective, CO₂-based systems are more suitable for cold and temperate regions, while R407C systems perform better in hot summer and mild winter regions.^{199,204} Additionally, replacing the PTC heating system on buses with a CO₂ heat pump system can increase the range by 10.37% to 12.90%. Electric motor waste heat recovery technology can enhance the performance of carbon dioxide heat pumps, increasing the COP by 6.97% to 11.13% and extending the range by 19.14% to 20.90%.²⁰⁰ Additionally, other scholars have conducted extensive research. For example, a comparison of the lifecycle carbon emissions of five low-GWP refrigerants (R1234yf, CO₂, R290, a binary mixture of CO₂ and R41, and M2) with R134a and R410A was conducted across 31 provinces in mainland China, and the results were visualized across seven different climate zones in China.²⁰¹⁻²⁰³

INTEGRATION OF MORE FUNCTIONAL REQUIREMENTS INTO THE TMS

TMS for battery and electronic components

Unlike ICEV, the TMS of NEVs must not only address the temperature and humidity regulation of the passenger cabin,¹⁷⁶ but also manage active heat dissipation, low-temperature preheating, waste heat recovery,¹⁸⁰ etc. As a core component of electric vehicles, the battery has witnessed continuous advancements in health status evaluation¹⁷⁹ and fault diagnosis.¹⁸² Moreover, to some extent, the thermal management of the battery (that highly affects driving safety) is the most important task of the EV's TMS because environmental conditions have great impacts on battery performance and stability, such as the capacity reduction in cold conditions^{76,177} and the risk of thermal runaway in hot conditions.⁷⁷

Taking lithium-ion batteries (the most commonly used option nowadays) as an example: various methods including air cooling,⁷⁸ liquid heat transfer,⁷⁹ refrigerant heat transfer,⁸⁰ phase change material,⁸¹ thermo-electric technology⁸² and heat pipe⁸³ have been introduced to carry on the thermal management task and remain the battery temperature in the range of 15-35°C.⁸⁴ In summary, in addition to the most conventional air cooling methods, which may no longer be sufficient to meet heat dissipation demand,⁹⁰ the remaining battery thermal management methods can be broadly categorized into two groups: a) approaches based on the vapor compression cycle, and b) approaches without the vapor compression cycle. As far as the current technological development is concerned, the former is more mature and widely adopted, serving as the primary solution; the latter also shows promising potential, which will be discussed in detail in next section.

Whether the refrigerant directly exchanges heat with the battery (direct cooling) or relies on a coolant as the intermediate medium (indirect-cooling), the vapor compression cycle actively produces cooling/heating capacities to regulate the battery temperature. Due to the elimination of the intermediate heat transfer medium, the cooling and preheating time of the battery in the direct-cooling system can be remarkably shortened. The refrigerant temperature remains constant during the refrigerant phase transition process. This is more conducive to the temperature uniformity within the battery. Therefore, direct cooling is considered by many researchers as a superior better battery thermal management method.⁸⁵ While the direct cooling method often delivers the optimal performance due to the high heat transfer coefficient during the two-phase evaporative process,⁹² it is important to note that many technical challenges remain in engineering applications.¹⁸⁸ Therefore, addressing the following three technical problems is essential to advance its implementation in the future applications:

A. The inlet and outlet qualities of the two-phase heat exchange section must be strictly controlled to ensure the entire heat exchange unit in the quality zone with the highest heat exchange coefficient;⁹³

B. The operating pressure of the refrigerant circuit is typically much higher than that of the coolant circuit, making the development of effective sealing solutions a critical technical challenge;⁹²

C. Considering the density difference between vapor and liquid phases, ensuring the uniform distribution of the two-phase fluid in the complex flow path remains a pressing issue.⁹²

The internal temperature uniformity of the battery pack has become a key

research topic at present, in addition to improving heating characteristics through modification to anode/cathode materials.⁸⁶ From the perspective of active thermal management, the importance of the optimization design of the coolant/refrigerant flow path inside the battery is increasingly recognized for its impact on operational efficiency and cost-effectiveness.⁸⁷ In traditional battery TMS, the coolant is typically enclosed within a horizontal heat exchanger plate (cold plate⁹¹) that is pressed against the surface of one side of the battery, facilitating contact heat transfer.⁸⁷ However, to achieve better temperature uniformity, the future coolant flow path must penetrate deeper into the battery pack in a three-dimensional configuration (even immerse the battery unit directly in coolant or oil^{88,175}), and achieve a more complex coupling on the three-dimensional structure, so as to sacrifice a certain pump work to achieve optimal battery thermal management.⁸⁹

Furthermore, it is important to note that with the continuous advancement and deployment of intelligent technologies such as automatic driving and vehicle network interconnection, new thermal control problems are emerging for the increasing number of high-power vehicle electronic components (ECU, radars, example).¹⁸⁶ The biggest feature of these components is their high power density coupled with a highly decentralized spatial layout. Therefore, managing their thermal needs through a single set of vapor compression refrigeration system would lead to a highly complex and intricate piping structure. Similar to the battery TMS, the TMS of electronic components is becoming a critical area of focus, and non-vapor-compression technologies are well suited to these tasks, as discussed in section: Pressure energy recovery technology in the expansion process.

Non-vapor-compression refrigeration technology

Whether utilizing direct cooling or indirect cooling, the cooling capacity of the VCR system is substantial and concentrated, making it well-suited for the centralized thermal management of high-power components. However, because the refrigerant needs to circulate and transfer heat in a closed flow channel, the components of the VCR system must be connected through pipelines. In systems with a small number of components, the system loop is relatively simple, as commonly seen in the vehicle TMS, which consists of an indoor heat exchanger for cabin cooling and a chiller for cooling battery and motor. However, as the number of components requiring thermal management increases and the highly decentralized spatial layout is presented, remaining the same VCR system will significantly increase the complexity of the system. Therefore, some non-vapor-compression refrigeration technologies with simple structures, small sizes, and reduced weights offer better adaptability for the application.

The heat pipe operates as a heat transfer medium through the liquid-vapor phase transition, where heat transfer is driven by natural convection, effectively functioning as a two-phase flow system without a pump. The heat pipe consists of a closed shell with a specific shape and filled with a two-phase refrigerant, and sometimes incorporates additional components such as metal fins, porous, or other substance to enhance the heat transfer rate. The specific geometry is designed to meet the complex application scenario, ensuring that one end of the heat pipe is placed in the hot environment before heat dissipation, and the other end is placed in the cold environment. During normal operation, the two-phase refrigerant evaporates in the high-temperature region and condenses in the low-temperature region, migrating continuously between the hot and cold ends due to its density difference, driven by gravity and natural convection. Through the efficient heat transfer between the two ends of the heat pipes, thermal energy can eventually be transferred from the high-temperature electronic components to the atmospheric environment.⁸⁷ Because of their simple structure, ability to handle complex geometric conditions, and no additional power or heat demand, heat pipes are poised to play an important role in the TMS of onboard electronic components.

On the other hand, similar to the liquid-vapor two-phase thermal management, the liquid-solid two-phase thermal management method (using Phase Change Materials) is also a promising latent heat storage solution for batteries/electronics. Considering the factors such as technology maturity, temperature range and cost, paraffin is commonly used phase change materials (PCMs) NEVs.⁹⁴ Composite phase change materials composed of paraffin, low-density polyethylene, and expanded graphite⁹⁵ has also been reported.

During operation, the PCM absorbs thermal energy from the components and melts. The components are insulated by the PCM solidification when the temperature is low. The PCM temperature does not change during the phase change process, it effectively maintains temperature uniformity across the entire component.⁹⁶ Furthermore, because PCM does not have overall migration or flow ability during the solid-liquid phase change process, it needs to be in close contact with the component ensuring a tight coupling with the three-dimensional structure. However, it should be noted that since the amount of on-board PCM is limited, the PCM thermal management capability diminishes once all the materials have completely melted. Therefore, PCM must be used in conjunction with other active cooling or heating means⁹⁷ to fully leverage its advantages.⁶¹ In summary, further development in on-board PCM needs to focus on the following aspects: a) increasing thermal conductivity and latent heat through composite materials; b) improving lightweight properties and electrical insulation; c) improving the longevity and reducing costs.⁸⁷ For instance, study has proposed a hybrid battery thermal management method by PCM with liquid and air based cooling, which significantly improves the system adaptability in response to fluctuating thermal loads.²¹⁴

In addition, the thermo-electric device, a specific material that can convert electrical energy into cooling/heating capacity based on the Peltier effect,⁹⁸ is widely considered as an excellent solution for localized thermal management. By adjusting the current or reversing its direction, it is easy to regulate the cooling or heating capacity as well as switch between cooling/heating modes.^{87,99} Given the stable supply of direct current in EVs, thermo-electric devices do not require additional transformers and rectifiers, making them well suited for addressing the distributed micro thermal requirements of individual components. However, it is worth noting that, although the thermo-electric devices are structurally simple, easy to use, compact, and highly adaptable to spatial constraints, they come with high costs and low efficiency. Hence, they are most effectively employed as an auxiliary solution, working in conjunction with other active cooling technologies to optimize performance.⁸⁷

Other solid-state refrigeration technologies (such as magnetocaloric,¹⁰⁰ electrocaloric,¹⁰¹ and elastocaloric¹⁰²) also have advantages including low noise, simple structure, good portability, accurate temperature control, etc. As their technical maturity is developing to a certain stage, they would also have a good potential for commercialization in the vehicle TMS.

In conclusion, the future TMS will likely be a complicated on-board energy system with a VCR cycle as the primary heating/cooling source. This system will integrate a variety of advanced energy transport, thermal management and heat transfer technologies operating collaboratively.

Integrated temperature and humidity management technology for EV thermal systems

Unlike the conventional ICEV, EVs, which continue to develop towards electrification and intelligence, have introduced more complicated and demanding requirements for TMS. These include various aspects such as energy saving, environmental protection, multi-functionality, high efficiency, noise reduction, cost-effectiveness and lightweight design, etc. However, due to the constraints of vehicle space and payload capacity, it is completely impossible to build a separate thermal management device for each component. In contrast, an integrated TMS can couple the thermal needs of all on-board components within a single unified system.¹⁰³ This concept has gained significant attentions and has been studied by researchers worldwide in recent years.^{104,105}

The first step in developing an integrated TMS is to consolidate the thermal management needs of key parameters, such as safety, stability, and driving range of the EVs. This involves a unified system loop (including necessary auxiliary equipment such as heat pipe) to address the multi-functional needs of passenger cabin temperature and humidity control, battery temperature, motor and electronic units temperatures.¹⁰⁶ This forms the foundational basis of vehicle TMS and is widely recognized by academic and industrial circles.¹⁰⁷

From a future development perspective, the vehicle itself can also be seen as a complicated energy system.⁶⁸ The optimal performance of an integrated vehicle TMS will depend on the effective matching and collaborative utilization among the multi-physical systems and multi-grade energy sources.¹⁹

Different from the independent design and independent operation of each part, the integrated vehicle TMS facilitates more efficient energy and information interaction between subsystems, thereby enhancing overall energy utilization efficiency. The key point in future research is the improvement of the basic energy utilization rate by enabling energy cascade utilization and minimizing energy dissipation across the space and temporal scale.⁹¹ The technical solutions to gradually achieve this goal include but are not limited to the following contents:

A. Waste heat recovery. During the EV operation, the simultaneous heating of the passenger cabin and cooling of the battery/motor system is often required, creating a typical thermal management challenge in TMS. In such scenarios, the heat pump cycle (a typical operating mode of TMS) can be used to recover waste heat from the battery/motor/electronics to heat the cabin. This process maximizes energy utilization efficiency and hence reduce energy dissipation.¹⁰⁸ Furthermore, in the vehicle energy system, there are various waste heat sources such as ventilation waste heat, braking energy, transmission loss, etc. which can be directly used for defrosting, defogging, cabin heating, battery preheating, etc. Therefore, the effective design and integration of waste heat recovery in the TMS is crucial for maximizing vehicle energy saving.¹⁰⁹

B. Two-stage compression. Typically, when operating in the double-cooling mode, there is a slight difference in the temperature ranges required by the passenger cabin and battery/motor/electronics systems. The air supply temperature of the cabin is around 10 to 15°C, while the battery coolant only needs to be cooled to 25-30°C¹⁰⁰. For VCR systems, when dealing with two heat sources of different temperature levels, the most energy-efficient running mode is the two-stage compression cycle.¹¹⁰ In such system, a portion of the refrigerant is not throttled to a lower pressure, allowing the cycle to be completed without consuming excessive compressor power.⁴³ Therefore, in vehicle applications with various energy levels, two-stage compression, or even multi-stage compression will become a primary trend for achieving multi-level thermal management.

C. Moisture equilibrium. Regardless of the TMS operation mode, condensate water is often generated at the heat exchanger terminal of the air cooling side (both indoor and outdoor). Meanwhile, the air relative humidity is typically reduced at the heat exchanger terminal of the air heating side. As a novel concept in heat and mass balance within the vehicle, if the condensate water could be redirected to the surface of the heat exchanger on the other side, it would not only significantly improve the heat exchange efficiency through evaporative cooling but also improve the cabin comfort in the indoor heating mode. This approach has significant potential for future development.

Notably, vehicle thermal and humidity coordinated management is a typical multi-functional and multi-objective technical solution, which must be based on the functionally integrated system architecture. To verify this objective, scholars have conducted extensive research on the integrated system process, and the results show that, under certain conditions, although the thermal and humidity management in coordination will consume more battery energy, the comfort level in the passenger cabin can be significantly improved. Therefore, it is certain to become an important branch of future technological development.²¹⁵

Thermal management systems for charging piles

Taking the most widely used lithium-ion battery as an example, the charging and discharging process of the power battery involves chemical reaction and ion migration inside the battery pack. It is inevitably accompanied by heat generation, the intensity of which can vary.⁵⁸ This heat release phenomenon is also the fundamental reason for introducing TMS in power battery packs.

On one hand, the battery heat generated in the discharge process (vehicle operation process) is significantly affected by the factors such as environmental temperature, vehicle speed, acceleration, and others. During this stage, the thermal management task must be fully supported by the vehicle TM as described in previous sections. On the other hand, with the continuous development of fast charging technology (3C or 4C fast charge in future), the power battery may generate an average heat output over 20kW⁷⁵ (at least five times the average heat output during the discharge process). This rapid heat buildup can cause the battery pack temperature to quickly rise above

50°C,^{70,91} which is unacceptable for battery safety. The fast charging technology not only creates new demands for optimizing charging strategies,¹⁷⁸ but also introduces new challenges for vehicle TMS.¹⁰¹ To some extent, even though the battery heat dissipation in fast charge process is the only demand for the on-board TMS, the thermal demand at this stage can exceed three times the total load encountered during normal driving process. This represents one of the most severe conditions for the TMS.⁷⁵ In other words, if the fast charge thermal management load is also completely realized by the on-board TMS alone, it would result in at least 60% of the TMS capacity being redundant during the normal driving process, leading to huge additional weight and volume for the vehicle.

From another perspective, the thermal management requirement of charging piles during fast charging has also become a prevalent problem.⁷⁵ Similar to the on-board TMS, the thermal management of charging piles also includes air-cooling,¹¹² liquid-cooling,¹¹³ and hybrid cooling systems with PCMs.¹¹⁴ All of which are designed to effectively regulate the temperature of both the charging pile and the charging cable.¹¹⁵ To fully cool the charging cable, many OEMs (Original Equipment Manufacturers) have taken the lead in proposing to expand the two-phase cooling loop to directly or indirectly contact the charging cable wires for efficient heat dissipation.¹¹⁶ Both theoretical¹¹⁷ and experimental studies¹¹⁸ have demonstrated the feasibility of this approach.

Looking ahead to future fast charge technologies, the authors emphasize the great significance of reducing the weight of the vehicle TMS if the excess heat generated by the on-board power battery can be cooled with the assistance of the charging pile TMS. Admittedly, it is necessary to provide a fast interface between the charging pile TMS and the vehicle TMS, ensuring seamless integration with the charging plug in the vehicle body. This integration still faces technical challenges, particularly in terms of sealing solutions and the standardization of refrigerants.

It is worth noting that the introduction of modules such as PCM and heat pipes into TMS will definitely increase the cost by about 10%. This is mainly due to the fact that the current industrial chain is not yet complete, and most experimental research is carried out based on customized samples for the trial production of the above modules. However, when mass production is achieved, all the above components can be charged based on weight and material cost, thus reducing the cost by 5 to 7%. Therefore, the cost increase brought about by introducing the above components is very small.

In summary, the future vehicle TMS should be a comprehensive multi-functional system based on the VCR cycle complemented by various thermal transport technologies, to address the increasingly complex thermal management requirements from the vehicle level. Furthermore, with the maturation of fast charging technology and the expansion of the charging pile market, the interaction between the vehicle side and the pile side at both the electrical and thermal levels has become an inevitable trend, gaining global recognition. This integrated approach is an effective way to advance the future safety, comfort, efficiency and low carbon EV industry, as shown in Figure 4.

THE SECONDARY-LOOP SYSTEM WITH A MODULAR STRUCTURE: THE FUTURE TREND OF VEHICLE TMS

Structure of the secondary loop system in vehicle TMS

With the increasing complexity of multi-functional requirements and the ongoing integration of various module components, the future vehicle TMS is expected far beyond the current imagination. Considering that the TMS system must interface with and exchange heat with the indoor environment, outdoor environment, battery, motor, etc., the vehicle TMS must be distributed throughout the EV's three-dimensional space. Due to the compact nature of EVs, the distributed TMS often needs to be connected through hoses and joints rather than soldering. As the system's complexity grows, the number of interfaces increases geometrically, which is the main reason for uncontrollable refrigerant leakage in the TMS, especially for natural substitutes such as CO₂ (operating at pressure over 10MPa) and R290 (flammability risks).⁴³

As discussed in previous section, the future TMS will feature a more complex pipeline loop structure. Establishing such complex high-pressure refrigerant flow paths is not the best choice in terms of economy and stabil-

ity.⁹⁴ Additionally, considering the flammability of R290 or other hydrocarbon refrigerants, it is not permissible for refrigerant loop to pass through the passenger cabin.¹¹⁹ Giving these reasons, constructing a secondary loop cycle consisting of a coolant and corresponding pipelines is an effective solution for achieving precise heat transfer between refrigerant and components.⁹⁴ In other words, through the flow and heat transfer processes of the intermediate heat exchange coolant, the physical separation between the refrigerant and the components/cabin can be completely realized, which ensures the safety and stability of the vehicle TMS. Furthermore, the working pressure of the coolant is generally much lower than the refrigerant system, reducing the complexity and cost of the pipeline system. As a result, by shifting the system complexity from the refrigeration cycle to the secondary loop, the refrigeration subsystem is greatly simplified, only comprising the compressor, condenser (or gas-cooler for CO₂), evaporator, and throttling device.¹²⁰ Meanwhile, many complex pipeline settings (such as four-way reversing valve, waste heat recovery loop, parallel component, defog, defrost and dehumidification, etc.) are all transferred to the secondary coolant system. Furthermore, due to the significant simplification of the refrigerant circuit, the refrigerant charging amount in the vehicle TMS with a secondary loop is also greatly reduced, which is particularly favorable for higher-cost refrigerants (such as R1234yf) and combustible refrigerants (such as R290).¹²⁰

It should be noted that the introduction of a secondary coolant loop inevitably increases the total heat transfer temperature difference between the refrigerant and the terminal objects (such as cabin temperature, battery temperature, etc.). Hence, compared with the direct system configuration, an obvious performance decline is generally observed in the secondary loop system.¹²¹ For example, experimental studies confirmed that the comprehensive COP (including heating and cooling) of the vehicle TMS could be reduced by 10% to 20% no matter whether R152a,¹²¹ R290,¹²¹ or CO₂¹²² are adopted as the working refrigerant. Furthermore, in terms of driving range, studies have shown that compared to direct systems, secondary loop system results in a driving range reduction of 0.46% to 4.95% under heating mode, and a reduction of 2.33% to 8.72% under cooling mode.¹³⁶

In summary, the future development of the secondary loop vehicle TMS should focus on the balance between performance and system safety/stability. Emphasis should also be placed on developing comprehensive evaluation criteria to effectively coordinate the synergistic impact of the above-mentioned factors and enhance the overall system efficiency. This approach will pave the way for improved prospects in the future development of the vehicle TMS.¹²³

Pressure energy recovery technology in the expansion process

The most promising refrigerant alternatives with good application prospects (R290 and CO₂) are well-suited for the secondary loop systems. Moreover, the future refrigerant alternative route is likely to be a hybrid strategy, where CO₂ is used in cold regions to leverage its heating capacity and R290 is used in tropical regions to ensure optimal cooling performance. This flexible approach to the secondary system and integrated component configuration offers significant advantages to vehicle manufacturers, as it allows for the same coolant circuit to be used across different regions, with only needing to replace the refrigerant handling module (e.g. compressor, etc.).

However, the performance degradation¹²² caused by the secondary loop and additional temperature difference must be solved to some extent. The relatively simple refrigerant circuit structure in the secondary system allows for the seamless integration of advanced performance improvement solutions such as expansion work recovery technology. In particular, for refrigeration with large pressure differences, such as the transcritical CO₂ cycle, expansion work recovery has considerable potential to improve system performance, often yielding gains of over 10%.⁴³ According to the current technical level, the expansion work recovery technologies with most industrial development prospects include ejectors, expander, and vortex tubes.⁴³

The ejector is a throttling mechanism with simple structure, no moving parts, low cost, and relatively high level of technical maturity. Its primary function is to convert expansion work into kinetic energy which is then used to increase the compressor suction pressure through vapor entraining and pressure diffusion. This process helps save compression work and improves

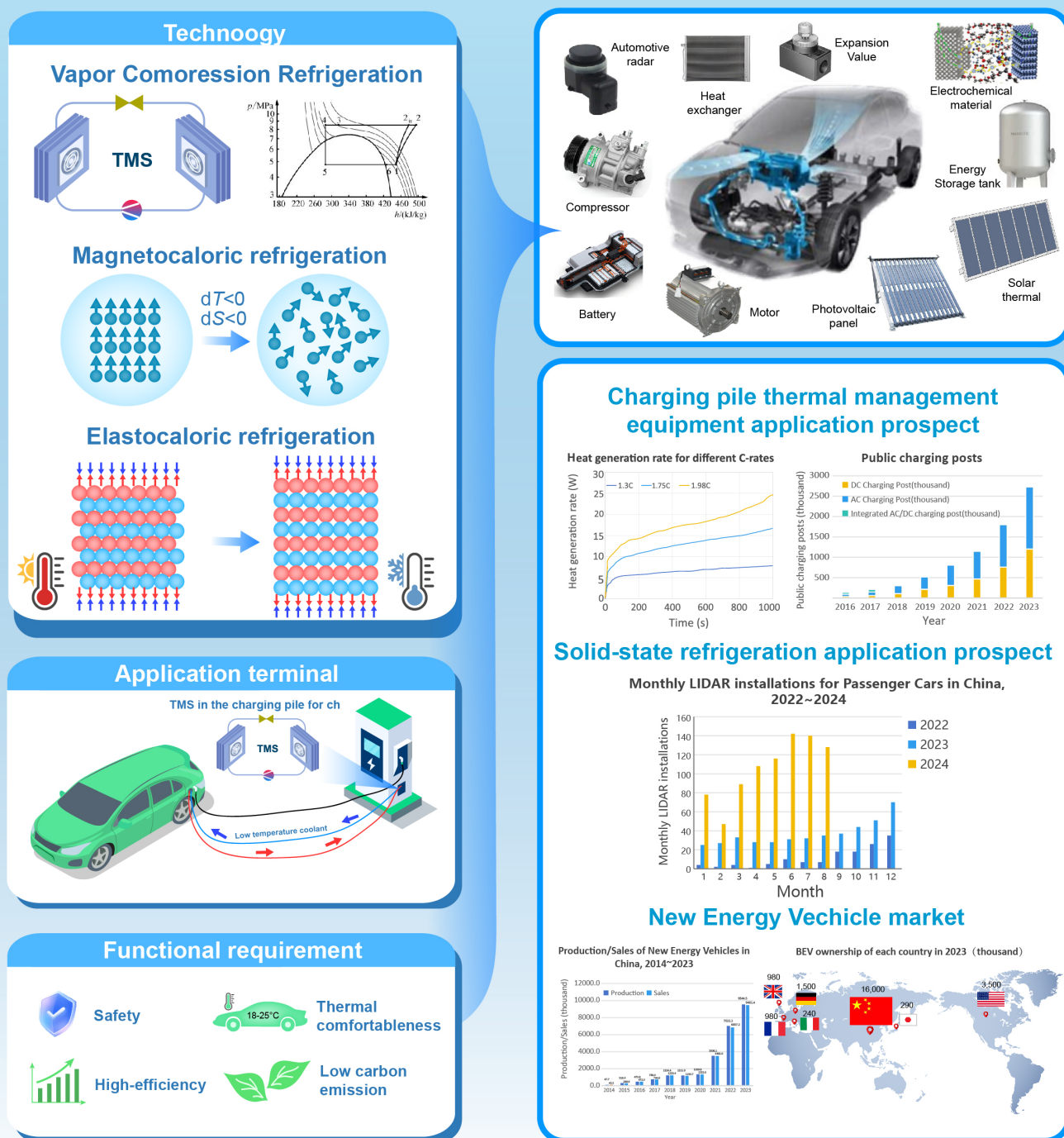


Figure 4. Future prospects of highly integrated vehicle TMS

system performance.^{124,125} It is reported that the performance of the ejector-based system could be enhanced by over 10% under the design operating condition. However, it deteriorates sharply (even worse than the baseline cycle¹²⁶) under conditions far from the design point.¹²⁷ Taking the transcritical CO₂ cycle as an example, the most industrialized application of ejectors is the commercial cold chain, which adopts multiple ejectors in parallel to achieve the effect of near-infinite flow regulation under different working conditions.¹²⁸ Considering the strong requirements for installation space and lightweight in the vehicle field, the potential for the ejector-based EV's TMS with drastic changes in working conditions remains limited until the breakthrough of adjustable ejector technology.¹²⁹ Additionally, the experimental

tests of the performance improvement effect of CO₂ ejectors on the TMS are carried by our research team in collaboration with Schaeffler, the results showed that the COP across the entire operating range increased by 5% to 15%.²¹⁷

The expander is a well-established performance enhancement technology in refrigeration systems. It can directly recover the potential energy from pressure difference into mechanical energy to generate electricity or complementarily drive the compressor, thereby reducing compressor shaft work, and improving the system performance.¹³⁰ Due to its ability to adapt to varying operating conditions, studies indicated that an expander can improve the system performance by 6-10% across a broad operating range.¹³¹ this adapt-

ability has led to the introduction of the expander concept into the vehicle TMS application to generate additional power.¹³² However, despite its potential, the expander faces several challenges related to mechanical strength, leakage, and friction loss caused by its moving parts. These issues must be addressed before the expander can be fully industrialized for use in the vehicle TMS.⁴³

The vortex tube is originally developed for air expansion refrigeration and has been introduced to VCR systems. It could convert the pressure energy into kinetic energy first and then bring additional cooling/heating capacities through a complex heat and mass transfer processes, thereby improving the system COP.¹³³ It is reported that CO₂ is always more suitable for vortex tube technology than other refrigerants because of its low molecular weight and low specific heat ratio,¹³⁴ which results in more intense energy conversion during heat and mass transfer processes. Thus, this technology has been theoretically introduced into the vehicle TMS with a 5~17% improvement over the baseline cycle under varying operating conditions.¹³⁵ However, the vortex tube technology remains the least mature of the three expansion work recovery methods. Therefore, significant future research and developments are required to improve the performance of future vehicle TMS.

Overall, the expander that show more significant performance improvements also lead to higher cost increases, while the performance improvement of ejectors and vortex tubes (with non-moving part) across the entire operating range is limited. Considering the large-scale production after the technology matures, the expansion machine should have a better development prospect. Meanwhile, since all the above three types of technologies can be applied in indirect systems with little impact on the system construction, the vehicle adaptability is relatively good.

Evolution and innovation of vehicle coolant

The thermal inertia of the vehicle thermal system is relatively large when the secondary loop technology is adopted, resulting in a slower heating process. This poses challenges for the coolant traditionally used in ICEV as the viscosity of the glycol-based coolant experience a sudden increase at low temperatures. Additionally, the coolant flow rate could be very low for a long time under the slow heating condition, which can hinder the heat transfer efficiency of various components.¹³⁶ Furthermore, the vehicle coolant is directly responsible for managing the battery thermal performance. Therefore, the selection of a new vehicle coolant must consider the adaptability of the battery's fast charging and discharging conditions. It can be concluded that the ideal coolant medium for EVs should have key characteristics such as high thermal capacity, low viscosity, nontoxic, low cost, etc.¹³⁷ Therefore, researchers suggest that, at the current stage of technology, a variety of coolant blending methods could be used to meet full-condition thermal and flow requirements.¹³⁸ For example, it is reported that the hydrofluoroether (HFEs, such as HFE 7000, HFE 7200, etc.), heat transfer oil (such as Dowtherm J), and other fluoride (such as Dynalene HC-50) are promising candidates.^{139,140}

In the future coolant application market, in addition to improve flow ability, enhancing heat transfer is also very important. It is well known that the thermal conductivity of the fluid could be significantly enhanced by adding metal particles.¹⁴¹ Based on this idea, researchers in recent years have recommended the use of high thermal conductivity nano-particles such as metals, metal oxides, carbon-based, metal nitrides, metal carbides, and nanocomposites¹⁴² in the liquid coolant (such as water, oil, acetone, ethylene glycol, and others).¹⁴³ This approach has demonstrated substantial improvement in the heat transfer properties of the fluid, with notable reduction in heat transfer temperature difference.¹³⁷ Thus, as long as the cost, heat transfer capacity, flow resistance, temperature range, safety, and other aspects can be balanced in the future, the advanced coolants are like to become the preferred choice in the EV's TMS.

In summary, as shown in Figure 5, the use of natural refrigerants in the EV's TMS has been an inevitable trend worldwide. However, with the increasing system complexity, natural refrigerants such as CO₂ and R290 are prone to leakage and pose safety risks. Therefore, the use of secondary systems offers many advantages, including the ability to accommodate different refrigerants, ease of maintenance, cost reduction, enhanced safety and reliability. Furthermore, to address the slight performance degradation caused by

secondary systems, pressure recovery technology has re-emerged as a promising solution. Based on the buffer of the secondary loop to the changes in external conditions, the operating conditions of the refrigerant subsystem in the TMS are relatively stable, which is particularly beneficial for the pressure recovery technology that always have more or less performance degradation under varying conditions. It is worth noting that the secondary system has a significant impact on the overall layout of the vehicle's piping, and thus requires collaborative development and structural design with the vehicle manufacturer. As a result, the transformation cost is quite high. However, on the other hand, the modular structure is conducive to standardized production throughout the entire industrial chain, and in the long run, it holds greater economic and industrial value.

THE SYNERGISTIC DEVELOPMENT OF INTELLIGENT TMS AND VEHICLE TECHNOLOGY

Generally speaking, the control logic of vehicle TMS is basically similar to that of other conventional thermal systems, which all adopt the exhaustive approach, formulating different control strategies under various operating conditions to ensure that the system maintains a relatively high performance level in as many predictable operating scenarios as possible. For instance, some studies adjust the battery thermal management strategies at different battery temperatures to ensure that the battery temperature uniformity remains within 1°C.²¹¹ However, when the system process becomes increasingly complex and the number of electric heating components significantly increases, the idea of exhaustive search is no longer applicable. Instead, it is necessary to explore more intelligent automatic control and optimization algorithms¹⁷² such as particle swarm methods etc.

Cloud information interaction technology

In the context of the intelligent TMS, a control logic framework has been proposed based on vehicle-edge-cloud collaboration¹⁴⁸ to address the future demands of intelligent vehicle modernization. Specifically, future intelligent vehicle TMS must facilitate vehicle-cloud collaboration in two key areas: information acquisition and intelligent computing, which will be outlined in detail below.

On one hand, the thermal demand of an EV's TMS significantly fluctuates due to transient operating conditions. Therefore, to effectively manage these various levels of thermal loads throughout the EV applications, the first priority is the accurate prediction of the dynamic thermal load at any given point during vehicle operation. The dynamic thermal load consists of loads from fresh air, passengers, vehicle walls, equipment, solar radiation, etc.³⁰ Therefore, in addition to the structural dimensions and thermal parameters of vehicle components, the operating environmental condition is important in predicting the real-time dynamic thermal load. Thus, the real-time data acquisition regarding climate information (ambient temperature, solar radiation intensity included),¹⁴⁷ navigation information (driving route, real-time traffic flow, traffic control, and estimated time included)¹⁴⁶ and traffic information (congestion degree, speed limit, curvature, slope, climbing, road type, vehicle position and other special road conditions included)^{144,145} is essential for dynamic load prediction. In the data acquisition process of the above-mentioned multi-source information, only a small portion is gathered by the vehicle sensors and radars, while the remainders must be sourced through wireless communication technologies.¹⁴⁸ Thus, the vehicle-cloud interconnection through fast information interaction technologies such as 5G is poised to become a key trend. This will enable advanced prediction of the overall driving cycles beforehand¹⁴⁸ with assistance from the increasing information acquisition channels. For instance, study has proposed an integrated power and thermal management (IPTM) strategy based on the multi-horizon model predictive control framework, enabling the real-time implementation. The proposed IPTM can leverage real-time information, such as ambient temperature, road slope, and preceding vehicle speed, to proactively optimize battery temperature and vehicle speed, ensuring efficient performance under varying driving conditions.²¹² Besides, by integrating the TMS strategy on Gaussian mixture model and soft actor-critical to recover the waste heat, the performance may have an enhancement of about 5%.²¹³

On the other hand, after acquiring multi-source information that is often irregular, unrelated, and non-standardized, it is crucial to filter the data,

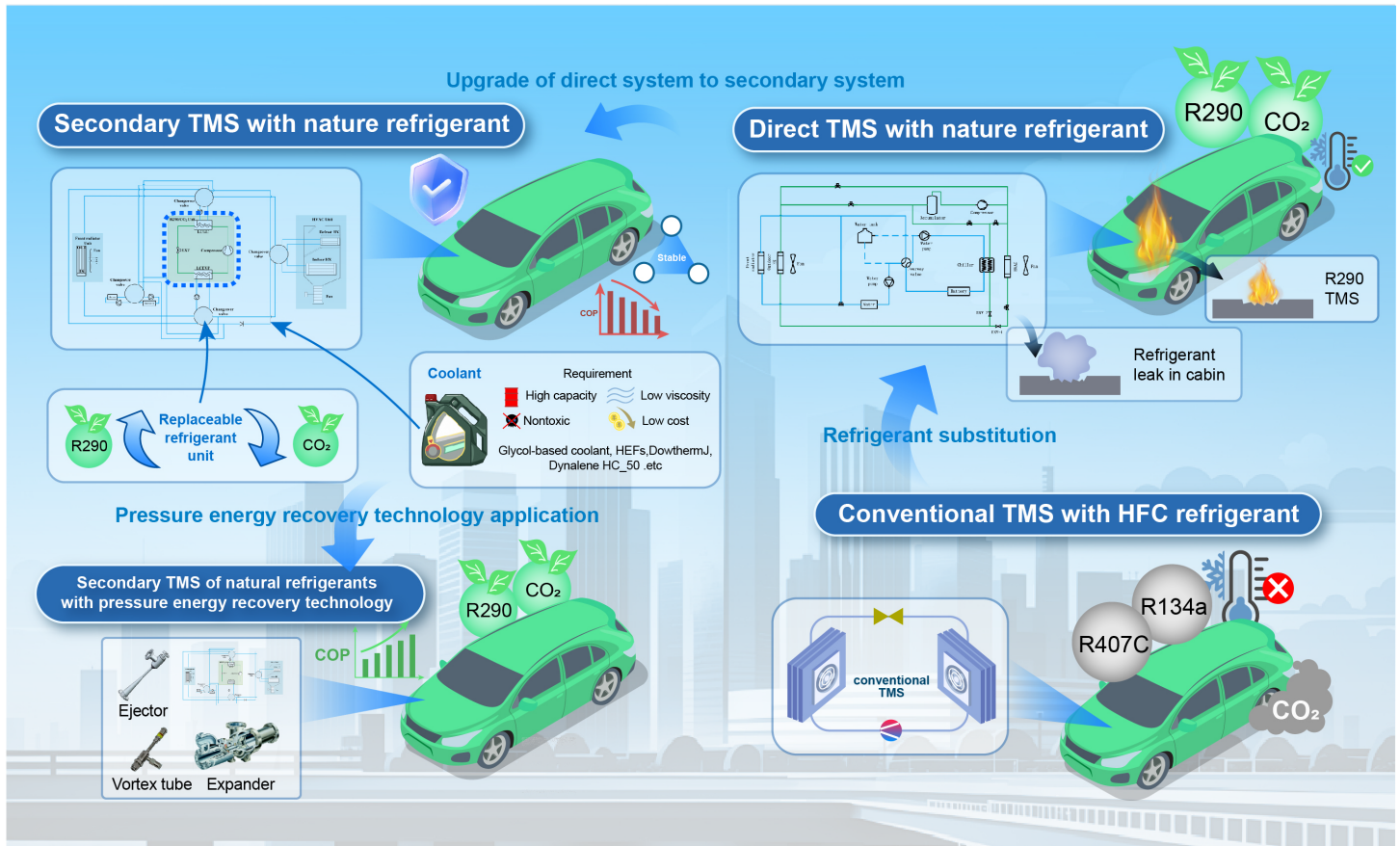


Figure 5. A conceptual framework for the potential of secondary loop with pressure energy recovery devices in TMS

predict the TMS energy demands, and determine the corresponding TMS control logic.¹⁴⁸ If driving cycles can be predicted beforehand and appropriate energy management strategies (EMSs) can be adopted, the working modes and battery SOC (State of Charge) reference strategy can then be adjusted promptly to optimize energy allocation and utilization.

However, dynamic traffic information and driving behaviors with high spatial-temporal variability, randomness, and uncertainty pose significant difficulty in the accuracy of both prediction and decision-making processes. Moreover, with the continuous improvement of vehicle intelligence, there is a growing need for higher prediction accuracy, and faster response times, which in turn dramatically increases the computational load.¹⁴⁸ To ensure real-time prediction and accuracy, the prediction and computation of dynamic vehicle requirements should be assigned to not only across the vehicle-mounted computing platform but also across the edge computing platform¹⁴⁹ (consisting of road-edge and vehicle-edge computing platforms) and cloud computing platforms simultaneously.¹⁴⁸ This approach emphasizes the control framework of the vehicle-edge-cloud collaboration as the future trend of intelligent TMS. Under this new computing framework, the vehicle and edge platforms are similar acting as local responders under the control of a central nervous system, which can rapidly and decisively make basic logical judgments to avoid local over-temperature and other issues. The cloud computing platform is equivalent to the global response made by the brain, which can optimize thermal energy allocation based on the entire driving cycle. This operating mode effectively integrates the quick response capability of the vehicle/edge platforms with the robust computing power of the cloud platform, while minimizing redundant information transmission, thus saving traffic and communication costs.¹⁵³ In other words, the future development of the vehicle-edge-cloud collaboration could establish an innovative framework for mass information fusion technology. In this framework, information with time series data,¹⁴⁹ multi-source parallel information,¹⁵⁰ and mixed data type¹⁵¹ could be assigned to different platforms according to specific requirements and computed simultaneously. The computed results could also be fast transferred to the corresponding demand side. In addition,

vehicle-level and regional road-level information is assigned to the vehicle and edge platforms for processing, respectively, while the cloud computing platform can be employed to analyze static and dynamic traffic information covering the city-level range, and the common data can be used as a local calculation basis for all vehicles on the same road section for reference.¹⁵⁴

Although vehicle-cloud collaboration is an important strategic direction for the NEV industry, this paper emphasizes its critical role in supporting intelligent vehicle TMS, as shown in Figure 6. accurate prediction of thermal load across all vehicle components throughout the entire driving process according to climate, navigation and traffic information, is essential to achieve truly intelligent thermal management in the entire time domain. This enables the optimization of thermal management energy consumption during the whole driving range. The importance can be seen in various common scenarios, including but not limited to the following:

A. Prior to embarking on a long trip in winter, the battery is preheated in advance to ensure that it maintains at a suitable temperature and an active state during the whole driving process, thereby improving battery discharge efficiency. Conversely, for short trips in winter, the battery preheating is omitted to prevent unnecessary energy consumption for battery heating.

B. When the battery is nearing depletion but the journey is still lengthy, the driver is prompted to initiate a fast charge. Prior to the charging process, the battery temperature should be pre-cooled to ensure the optimal thermal conditions and safety during the fast charge process.

C. When the battery and motor are expected to operate at high power levels (such as congested sections, climbing sections, etc.), pre-cooling of the battery/motor should be performed in advance to prevent short-term over-heating.

The rapid development of intelligent and connected technologies has contributed toward the acquisition of multi-source information, prediction of driving cycles, and improvement of control capabilities. These development enables NEVs and their thermal management systems to operate much more efficiently. Many scholars are researching methods of using vehicle-cloud cooperative technology for battery thermal management.¹⁸⁹ For instance,

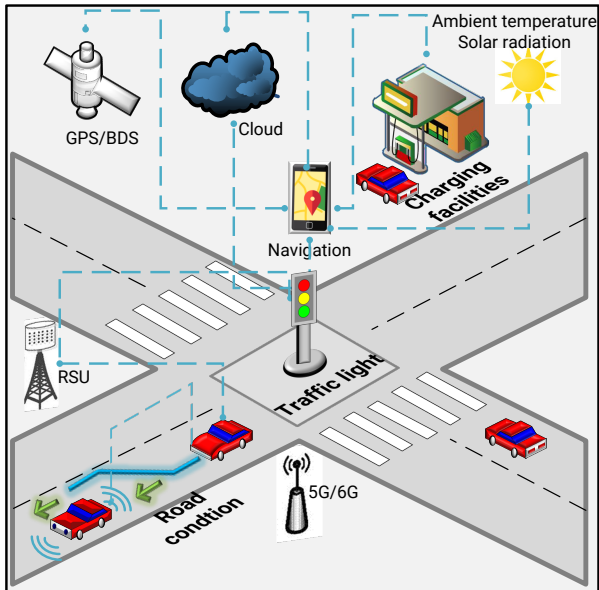


Figure 6. Schematic diagram of the vehicle-edge-cloud collaboration framework

EXCEEDDATA Corporation has developed a vehicle-cloud integrated Data Engine, which has been applied to thermal management systems. In this application, driver behavior is mapped to battery data through cloud-based analysis. Subsequently, the thermal management model is optimized via cloud training and then deployed to the vehicle's thermal management system through the Data Engine. The vehicle-cloud collaborative application has demonstrated significant energy savings: under high-temperature conditions, projected energy savings reach 6.6% within 10 km, 3.8% for 10–20 km, and 2.3% beyond 20 km. Corresponding energy savings under low-temperature conditions are 5.7%, 2.8%, and 1.2%, respectively.¹⁹⁰ However, future intelligence still needs to be verified by a large number of engineering practices over an extended period before they can be fully integrated into daily life.

Energy hub for vehicle TMS

The intelligent TMS can be generally divided into two key aspects: from a micro point of view, the EV itself is a complicated local energy system. Therefore, the optimal control of the TMS, including the passenger compartment, electric motor, battery, electronic units, and transformer converter, needs to satisfy their respective energy requirements while minimizing energy consumption. Hence, it is particularly important to achieve a good energy distribution among these components in the time domain.¹⁸³ From a macro perspective, various dynamic thermal loads can be accurately predicted and managed through operating environmental parameters (such as climate, navigation and traffic information)^{144–147} as well as structural dimensions and thermal parameters of the vehicle components.¹⁵²

The optimal energy allocation for vehicle TMS throughout the entire driving cycle can be treated as a nonlinear, time-varying optimization problem with multiple constraints and control objectives. The solution involves determining the distribution of the thermal management requirements over the time domain as well as establishing a trade-off between real-time prediction and accuracy. This balance is essential for assessing the operational status (including security, economy, power performance, and ride comfort) of TMS at different stages. To achieve this target, the TMS algorithm must evolve from traditional instantaneous optimization to rolling optimization and, ultimately, to global optimization.

As a complicated local energy system, the transient optimization of energy distribution and time-domain optimization of energy scheduling is always of great importance for enhancing EV driving range.¹⁵⁵ As for the transient optimization of energy distribution, for instance, when the battery temperature approaches the upper limit, it is necessary to prioritize battery cooling for safety reason even at the expense of comfort and power requirements. In terms of the time-domain optimization of energy scheduling, for instance, considering the serious attenuation of battery SOC performance under low-

temperature conditions, warming up the battery in advance may offer a greater driving range than simply turning off all the non-power electric equipment such as cabin heating. All such transient and dynamic decisions must be finally governed by advanced intelligent algorithms and more precise models.¹⁵⁶

The thermal management control architecture of EVs mainly adopts Proportional-Integral (PI) control based on the requirements of the passenger cabin and battery. In this approach, the set temperature is used as the target for the PI controller, and the error between the measured and the set values is minimized by adjusting the actuators, such as valve opening and compressor speed, etc. Other parameters, such as indoor airflow, are usually adjusted either through a calibration chart or manually by the passenger.

However, PID and similar control architectures have several limitations. Since all control target parameters are pre-defined in an offline state, they are unable to achieve real-time intelligent control that minimizes the total power consumption of the TMS, and therefore cannot improve driving range. Additionally, the power consumption of components such as compressors, fans, and pumps cannot be effectively coordinated, resulting in significant energy waste. Thus, the offline control mode based on PID feedback logic has been quickly replaced by intelligent online control logic, such as the Model Predictive Control (MPC) method,^{158–160} which has emerged as the most competitive intelligent control strategy in the TMS and has attracted much research interest.¹⁶¹ Furthermore, drawing from its success in other industrial applications, MPC always outperforms traditional PID in scenarios involving: a) multiple inputs and multiple outputs, b) conflicting objectives, c) numerous constraints to be met.¹⁵⁷

The core concept of the MPC method is to provide optimal operation inputs based on a built control-oriented model and a defined objective function, while satisfying a set of constraints.¹⁶² The control-oriented model comprises several equations and constraints, which should capture the system's dynamic behavior accurately with a relatively simple structure.¹⁵⁹ The objective function generally aims to minimize the total TMS power consumption, maximize the vehicle's driving range, or incorporate a more sophisticated objective function such as traffic information, etc., while maintaining the cabin and battery temperatures at the set point (or within a certain range). Then, the MPC controller can provide optimal solutions for a finite preceding horizon according to the control-oriented model, objective functions, and constraints. Generally, only the current step solution is implemented in the control system, and the optimization process is repeated at each subsequent step using updated states. This results in a receding horizon control strategy that continuously optimizes the system. Therefore, the three key elements of an effective MPC algorithm are the objective function, constraint conditions, and a set of accurate control-oriented model.⁶⁹

An efficient control framework and control-oriented model should prioritize both usability and feasibility. Therefore, the following two parts of work are generally required in the specific operation: a) as the core of the whole control logic, the MPC algorithm predicts the optimal state of the real-time control object, while the traditional PI control continues to manage the equipment according to the predicted values, thus synthesizing the advantages of both PI and MPC methods; b) the gray box model¹⁶³ is commonly used in MPC, where a concise physical framework can use the white box model, but the complicated physical processes of the partial differential equations are usually replaced by the data-driven black box model.¹⁶¹

Recently, the authors proposed a new control method based on the energy hub of the vehicle TMS using a real-time nonlinear MPC algorithm, as shown in Figure 7. This proposal addresses a finite-horizon optimal control problem (OCP) incorporating both spatial and temporal scale based on multi-objective cost function, several constraints, and a precise prediction model. In the developed control framework, the MPC can directly provide the optimal cabin air mass flow rate, coolant mass flow rate, and compressor speed to the blower, pump, and compressor, and the EEV opening of the cabin and chiller loop is adjusted based on the set refrigerant superheat via a PI controller (the variation rules of the above parameters can often be described by high order polynomials¹⁶⁵). The control-oriented model is validated using a high-fidelity physical model built in Dymola.¹⁶⁴ The proposed control framework successfully reduces the total power consumption of the blower, pump, and compressor under a basic application on the premise that the cabin and

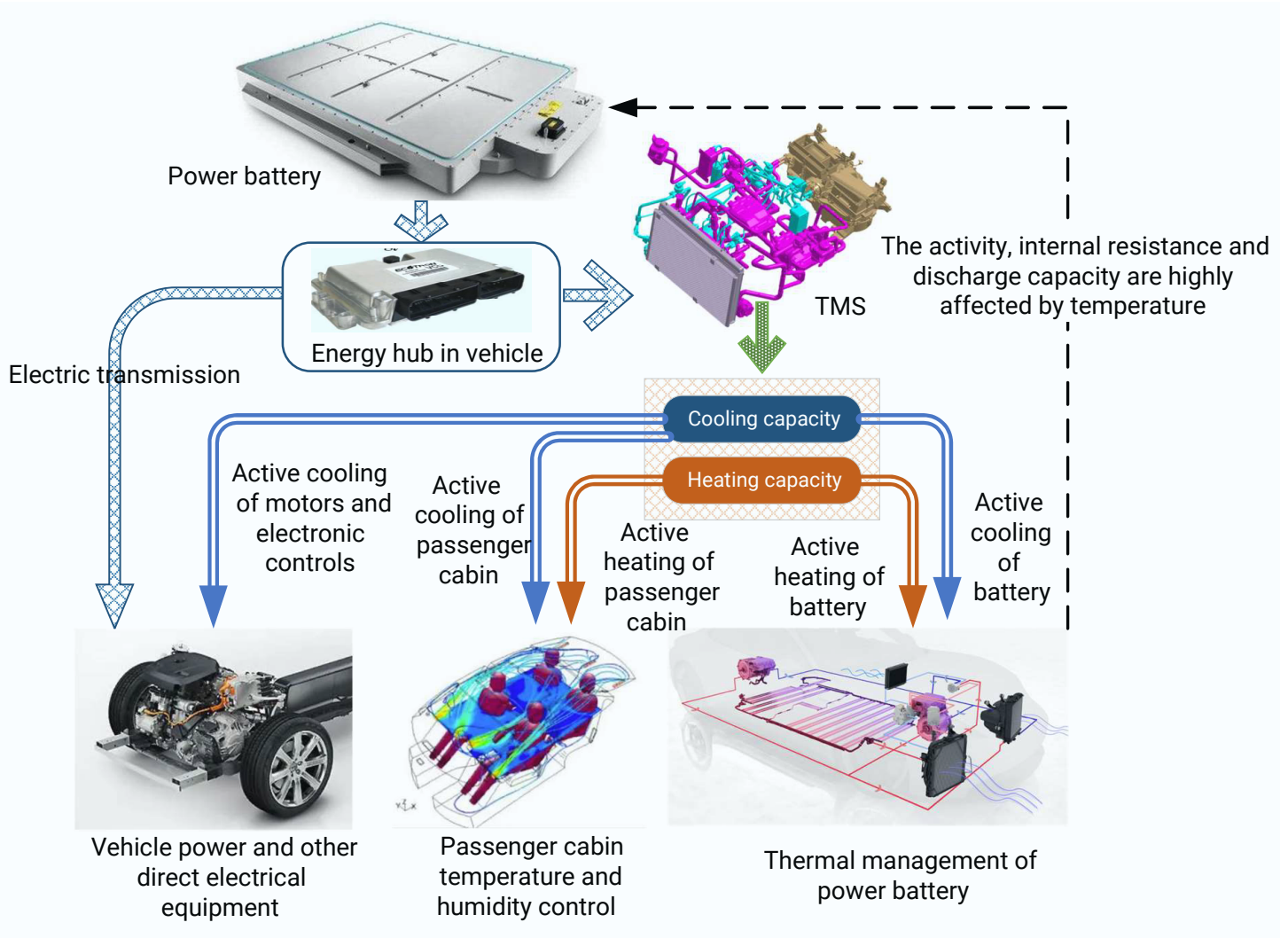


Figure 7. The energy hub system for vehicle thermal management

battery temperature are well maintained. As the intelligence level of the MPC controller¹⁶² increases, the energy hub can accurately predict the state and performance of the TMS based on the current measurement parameters of the vehicle, enabling thermal management strategies for the cabin, battery, motor, and electronics to achieve the final goal of saving battery energy consumption. As a result, improvement could be obtained by coordinating the power consumption of various components and minimizing overall power usage.¹⁷³

The new thermal management control architecture based on the TMS energy hub demonstrates great potential for application. It is expected to further improve EVs' driving range and provide more optimized control strategies to the TMS to meet the evolving needs of the future EV market. It is worth noting that the computing power of the vehicle's computing platform should also be greatly improved, which is likely to cause extra thermal load for the TMS. Thus, while achieving the energy-optimized allocation through complex computation and algorithms it is crucial to address the additional energy consumption imposed by the various vehicle computing platforms. Striking a balance between these two factors presents a practical challenge that needs to be considered and managed by the energy hub itself. It is worth noting that with the intelligent development of electric vehicles, the on-board computing power has significantly increased. Therefore, the hardware cost of the TMS energy hub (such as circuits and electrical components) can be disregarded. As a result, the vehicle adaptability of this technology is extremely superior.

FUTURE DEVELOPMENT PERSPECTIVES OF TMS

Advanced methods for performance evaluation

The vehicle TMS operates as a complex refrigeration cycle. Existing research continues to apply evaluation standards from the refrigeration field to assess the vehicle TMS energy efficiency. However, as an important part of the integrated EV, the TMS consumes a portion of the battery energy, and plays a vital role in ensuring the power level, stability, safety and thermal comfort for EVs. For instance, if the TMS consumes more energy (or worse TMS performance is obtained) but better working temperature and working state of the battery pack (or other components) are maintained, it is important to adopt a more comprehensive approach for overall performance evaluation. This requires developing a scientifically sound method that balances these trade-offs. To respond to this need, researchers have shifted towards using the impact of the TMS on driving range to replace the traditional evaluation methods such as COP.¹⁶⁹⁻¹⁷¹ The absolute reduction in vehicle range caused by the TMS is often meaningless. New methods such as the range attenuation rate or the energy consumption coefficient of the TMS are increasingly being adopted to assess its performance more effectively in the future.

The range attenuation rate (θ) represents the actual range of the vehicle under a standard range test (CLTC, or NEDC, or WLTC etc.) from SOC of 100% to 0% after the TMS activated (R_{TMS-on}), compared to the range without the TMS ($R_{TMS-off}$) activated. It can be written as:

$$\theta = \frac{\sum_{SOC=0}^{SOC=100} R_{TMS-on}}{\sum_{SOC=0}^{SOC=100} R_{TMS-off}} \quad (1)$$

The energy consumption coefficient (ψ) represents the proportion of the TMS energy consumption ($\dot{W}_{TMS}$) to the total energy consumption of the whole vehicle ($\dot{W}_{tot}$). The test is conducted under standard range test condi-

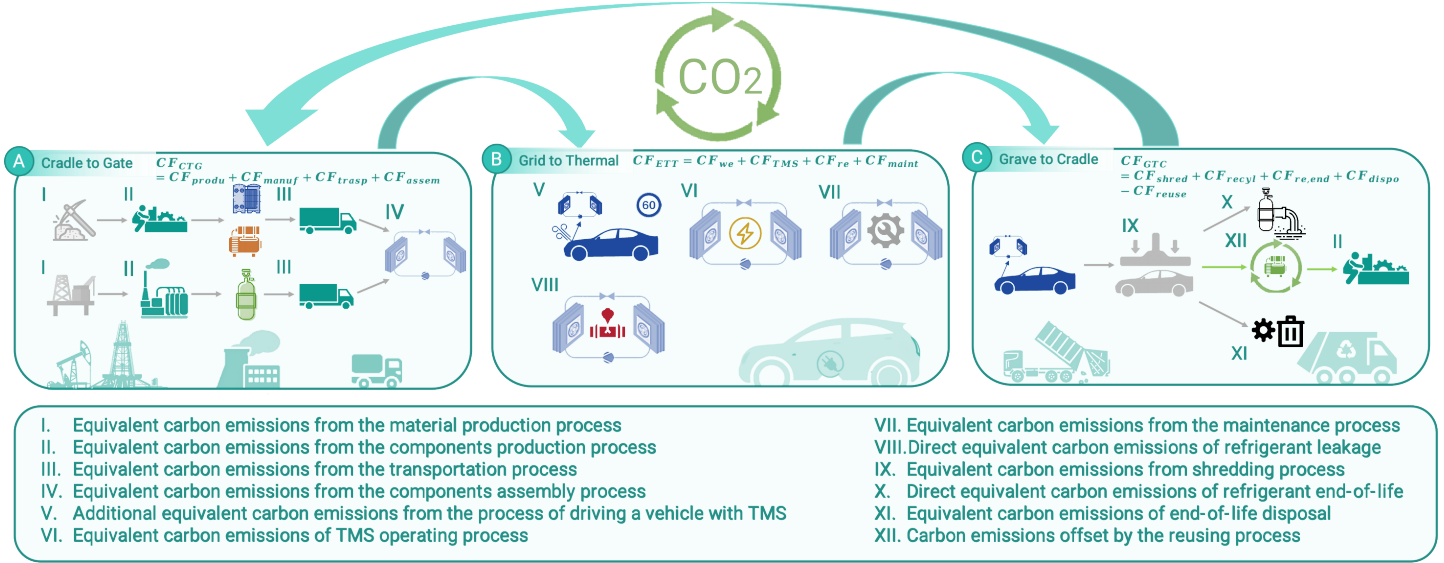


Figure 8. Equivalent carbon emission factors of the TMS

tions from a SOC of 100% to 0%. It can be written as:

$$\psi = \frac{\sum_{SOC=100}^{SOC=0} \dot{W}_{TMS}}{\sum_{SOC=100}^{SOC=0} \dot{W}_{tot}} \quad (2)$$

Given that the significant impact of operating mode and ambient temperature on the performance of the TMS, the seasonal energy consumption coefficient of the TMS should be determined through three steps: a) Obtain precise values of the range attenuation rate (or energy consumption coefficient) under different operating modes and ambient temperatures; b) Aggregate the actual operational requirements in the application background according to the historical climatic conditions; c) Estimate the comprehensive energy efficiency level of the TMS over its entire service cycle by integrating the proportions of operating modes and ambient temperatures. This can be written as:

$$\psi_h = \frac{\sum_{T=-30}^{T=7} \psi_T \cdot H_T}{H_h} \quad (3)$$

$$\psi_c = \frac{\sum_{T=35}^{T=45} \psi_T \cdot H_T}{H_c} \quad (4)$$

where ψ_h and ψ_c represent the seasonal energy consumption coefficients for heating and cooling modes, respectively; ψ_T represents the energy consumption coefficient under a specific ambient temperature; H_T represents the number of hours the vehicle operates under a given ambient temperature; while H_h and H_c represent the total operating hours during heating and cooling seasons, respectively. It should be noted that the ambient temperature upper and lower limits for the cooling/heating modes should be adjusted according to the actual operation area.

The above two evaluation factors are used to evaluate the performance of R134a, R290, and CO₂ TMS, and the data are shown in Table S3 & S4. In the cooling conditions, R134aTMS performs well, and R290 is more favorable compared to CO₂. However, at the extremely cold temperature of -30°C, close to 70% of the driving range can still be guaranteed with CO₂ TMS, significantly alleviating users' range anxiety, yet less than 50% with R134aTMS. Depending on the seasonal energy consumption coefficient in typical cities in five climate zones of China to compare two refrigerant substitutions, R290 performs better in the cooling season, while CO₂ performs better in the heating season especially in Heilongjiang. The comparison result shows that CO₂ is more suitable for cold regions, and the R290 performs better in hot or mild regions, suitable alternative refrigerants can be selected of each region according to local climates.

With the progression towards carbon neutrality, the equivalent carbon emission factor will become an important evaluation index for the future TMS.¹⁷⁴ The equivalent carbon dioxide emissions generated by the TMS in the whole life cycle to meet the cold and hot demands of the vehicle is defined as the whole life cycle carbon emission factor (LCCF). The LCCF consists of three parts: the equivalent carbon emission from Cradle to Gate (CF_{CTG}), the equivalent carbon emission from Grid to Thermal (CF_{ETT}), and the equivalent carbon emission from Grave to Cradle (CF_{GTC}), as written below and shown in Figure 8:

$$LCCF = \frac{CF_{CTG} + CF_{ETT} + CF_{GTC}}{D_{life}} \quad (5)$$

$$CF_{CTG} = CF_{produ} + CF_{trasp} + CF_{manuf} + CF_{assem}$$

$$CF_{produ} = \sum_i CFC_{p,i} \cdot M_i$$

$$CF_{trasp} = \sum_i CFC_{t,i} \cdot M_i \cdot D_i + \sum_j CFC_{t,j} \cdot j \cdot D_j$$

$$CF_{manuf} = \sum_i CFC_{m,i} \cdot M_i$$

$$CF_{assem} = CFC_a \cdot M_{TMS} \quad (6)$$

$$CF_{ETT} = CF_{TMS} + CF_{re} + CF_{we} + CF_{maint}$$

$$CF_{TMS} = CFC_{elec} \cdot \sum_N \sum \frac{FEC \cdot \eta}{N} \frac{NC_{bat} \cdot \zeta \cdot DOD \cdot \psi}{(1-r)^N}$$

$$\eta = f(SOC, DOD, C, T)$$

$$\zeta = f(SOC, DOD, C, T, CL)$$

$$CF_{re} = Q \cdot (GWP + Adp \cdot GWP) \cdot (N\beta)$$

$$CF_{we} = \frac{M_{TMS}}{M_{tot}} \cdot CFC_{elec} \cdot \sum_N \sum \frac{FEC \cdot \eta}{N} \frac{NC_{bat} \cdot \zeta \cdot DOD \cdot (1 - \frac{\psi}{(1-r)^N})}{N}$$

$$CF_{maint} = CFC_m \cdot U_{TMS} \quad (7)$$

$$CF_{GTC} = CF_{shred} + CF_{recyl} + CF_{re,end} + CF_{dispo} - CF_{reuse}$$

$$CF_{shred} = CFC_{shred} M_{TMS}$$

$$CF_{recyl} = \sum_i CFC_{r,i} M_{r,i}$$

$$CF_{re,end} = Q(GWP + Adp \cdot GWP) \beta_{end}$$

$$CF_{reuse} = \sum_i CFC_{p,i} M_{r,i}$$

$$CF_{dispo} = \sum_i CFC_{d,i} (M_i - M_{r,i}) \quad (8)$$

The total driving range (D_{life}) is written as:

$$D_{life} = \sum_N \sum \frac{FEC \eta}{N} d \zeta DOD (1 - \frac{\psi}{(1-r)^N}) \quad (9)$$

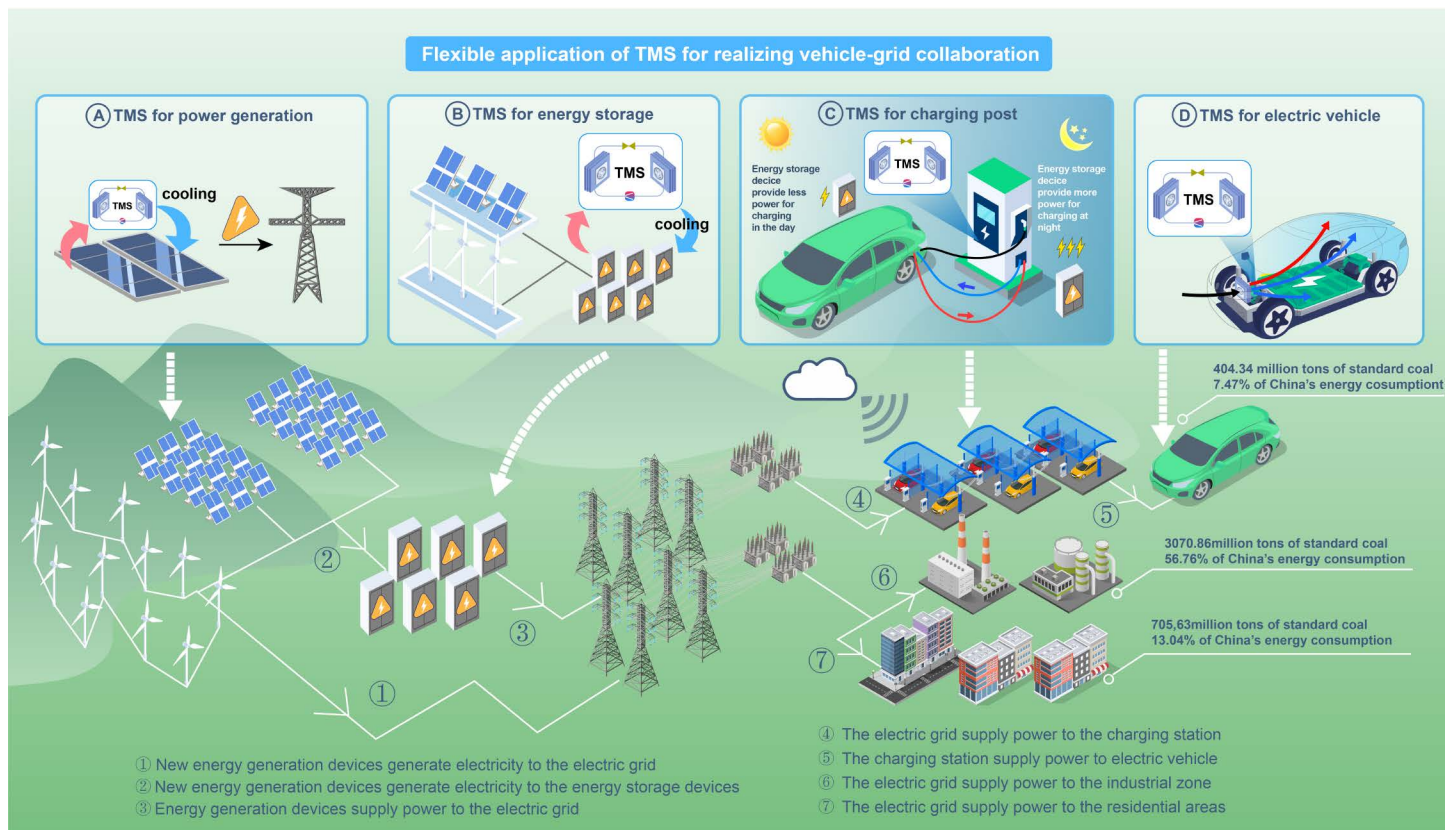


Figure 9. Flexible application of the future vehicle TMS for realizing vehicle-grid integration

All these nomenclatures in the above formulas are shown in Table S5.

LCCF evaluation method, combined with the climate temperatures of different regions, is utilized to calculate the carbon emission values of different TMSs. The detailed data are presented in two parts: direct equivalent carbon emissions and indirect equivalent carbon emissions as shown in Table S6 (national average grid carbon emission factors are used in carbon emission calculations for different countries). Both the alternative refrigerants R290 and CO₂ are effective in reducing the direct carbon emissions of the TMS by nearly 1500kgCO₂eq. Conversely, the indirect equivalent carbon emissions are influenced by the local climate, and in line with the energy efficiency performance that R290 and CO₂ are suitable for different regions that CO₂ is more suitable for cold regions, and the R290 performs better in hot or mild regions.

The ultimate form of EV's TMS

Regarding the thermal management technologies from OEMs' open information, a lot of advanced technologies are conducted, which not only focuses on optimizing battery performance²⁰⁵⁻²⁰⁶ but also pursues thermal management technology upgrades to achieve structural optimization, cost reduction, efficiency, and energy saving. The TMS of Tesla model Y can realize waste heat recovery in the thermal management circuit based on the R1234yf refrigerant heat pump air conditioning system, supplemented by low-pressure PTC and refrigerant recirculation technology, which improves the heating efficiency at low-temperature environment, and in turn improves the driving range of the vehicle. In addition, a large integrated eight-way valve (Octovalve) dynamically combines the heat pump air-conditioning system, electric drive, and battery thermal management circuits. Moreover, motor blocking technology, intelligent thermal management algorithms, and calibration technology are also important features.²⁰⁷ The TMS of BYD "Seal" can cope with all 8 modes combined with heating/cooling of air conditioning and heating/cooling of the battery through the switch combination of nine-way valve (Nonavalve) and the battery adopts the refrigerant direct cooling system.²⁰⁸ In addition, CO₂ can be used as a refrigerant in the Volkswagen ID4 heat pump air conditioning system, giving full play to the advantages of CO₂'s heating performance.²⁰⁹ China Changan Automobile Group also exhibits an

R290 all-in-one integrated unit, signalling that the system has entered the application phase.²¹⁰ Additionally, Chinese IM Motors achieves the real vehicle tests of the safe system operation and passenger comfort by using a six-way valve. The results show that, by adopting more advanced technical solutions such as waste heat recovery, a 3% to 5% increase in the vehicle's driving range can also be achieved on actual vehicles.²¹² The various new TMS are proposed towards "new four modernizations": green and efficiency, functional integration, modular structure, and intelligent control.

However, the development of thermal management systems is still far from mature at present. The ultimate form of an EV's TMS should be considered from two key perspectives. On one hand, as discussed in previous sections, within a single vehicle, the TMS should adopt environmentally friendly refrigerants and secondary loops to improve environmental protection, enhance safety, and reduce cost. The integration of advanced technologies such as thermal energy storage, solar energy, pressure energy recovery, non-vapor compression refrigeration, etc. should be prioritized, all while aligning with integrated system structure to optimize performance and ensure system stability. Additionally, as the TMS becomes increasingly complex, the real-time optimization control logic with MPC as its core will be essential to ensure the system in an optimal energy distribution state throughout its operation. To achieve this, the adoption of intelligent predictive and coordinated control strategies is becoming increasingly important. Furthermore, future TMS development will benefit significantly from the incorporation of advanced control algorithms and predictive modeling techniques. For instance, combining MPC with real-time data-driven strategies can enhance thermal management precision and energy efficiency, particularly under dynamic driving conditions or complex environmental scenarios. By predicting thermal loads and usage patterns in advance, such predictive control methods help to preemptively adjust system states, thereby reducing response lag and unnecessary energy consumption.

On the other hand, EVs can be treated as substantial energy storage devices serving as substantial reservoirs of flexibility within the evolving civil power system,¹⁶⁶ as shown in Figure 9. First, the decommissioned battery from EVs can be repurposed as energy storage units, facilitating the flexible integration of new energy power sources. Second, after realizing the combi-

nation of pile-side and vehicle-side cooling systems, the rapid adoption of fast charging technology is essential. This advancement might change the intervention time of EVs as electricity storage assets in the urban power system with a shift from predominantly night-slow charging to daytime fast charging. In parallel, the integration of TMS with vehicle-level energy management systems (EMS) offers an important opportunity to optimize energy distribution holistically. By synchronizing TMS operations with battery management, drive system demands, and even interactions with external power grids, a comprehensive EMS can achieve coordinated optimization across a wide energy domain. Future research could explore joint optimization frameworks for thermal and electrical energy management, constructing adaptive control strategies that concurrently address both domains. This approach is expected to enhance individual EV performance and contribute significantly to the broader energy ecosystem—especially under the emerging paradigm of vehicle-grid interaction.

Taking China as a representative case, it has the world's largest number of electric vehicles, totaling 31.4 million. In 2022, transportation energy consumption accounted for 7.47% of China's total energy consumption.¹⁹¹ Therefore, electric vehicles, which serve as critical grid-edge nodes for energy utilization, storage, and bidirectional power flow, stand as one of the most essential components in China's energy transition. Based on this, the Chinese government has implemented policies to vigorously develop new battery energy storage technologies related to electric vehicles,¹⁹² including thermal management and energy control systems. This initiative aims to accelerate the energy transition and facilitate the achievement of the "dual carbon" goals.¹⁹³ EV batteries possess the capacity to store intermittent renewable energy generated from photovoltaic and wind power sources. Relevant research indicates that the energy storage potential of 22.7 million EVs could satisfy 2.7 TW of new energy storage demand,¹⁹⁴ thereby supporting further deployment of intermittent renewable energy infrastructure. Furthermore, EVs can contribute to load regulation and peak shaving on the demand side of the energy system. Through well-designed vehicle-to-grid strategies, the peak-valley difference can be reduced by over 31.5%, while load fluctuations may decrease by more than 37.1%.¹⁹⁵ In the processes of energy storage or peak shaving, the role of thermal management technology is to regulate temperatures during these operations. This ensures operational safety while maintaining batteries in optimal condition for either energy storage or load regulation.¹⁹⁶ Therefore, it is imperative for researchers and policy makers to conduct comprehensive research into the macro effects of the TMS development under the broad framework of vehicle-grid integration.

CONCLUSION

This paper comprehensively reviewed the state-of-the-art in EVs and the evolving development of the EV TMS within the context of the global efforts toward carbon neutrality. The development of EV TMS is increasingly aligned with the "new four modernizations" – focusing on green and efficiency, functional integration, modular structure, and intelligent control.

A. In terms of the reduction of strong greenhouse gases, CO₂ and R290 are currently the predominant choices, with various forms of mixed working fluids serving as complementary alternatives. The next-generation technology trajectory will be mainly affected by relevant standards, regulations, and policies, as well as the diverse functional requirements of EVs in different regions. With the increasing demand for energy utilization efficiency in the TMS, the efficient coupling of subsystems can maximize energy efficiency. Hence, the integration of heat pumps, waste heat recovery, solar energy, energy storage, and their cross-coupling will become central to future development in the EV TMS.

B. The functional integration of next generation of EV TMS must address multiple goals including vehicle safety, power performance, endurance, thermal comfort, etc. Thus, effective temperature management of all key components will ensure a high safety margin, while precise temperature management and energy allocation across all power equipment will enhance system performance. Additionally, real-time management will cater to the diverse hot and cold needs for both passengers and vehicles.

C. As the TMS becomes increasingly complex, the need for a modular TMS structure has become urgent. This approach is mainly reflected in two aspects: component integration and functional integration. The implementa-

tion of the secondary loop construction enhances the versatility of the TMS across different models and brands while promoting a more concise TMS structure. Furthermore, the performance degradation can be solved by incorporating the expansion energy recovery technologies.

D. By leveraging MPC algorithm, combined with real-time climate/navigation/traffic information and diversified user characteristics, the refined and diversified predictive control of the EV TMS could become feasible. Intelligent control might become an essential part of the EV TMS in the future. Therefore, a more scientific and comprehensive TMS performance evaluation mechanism should be adopted, taking into account both instantaneous and full driving cycle levels.

In summary, the ongoing development of the EV TMS, driven by these key technological trends will play an important role in enhancing the efficiency, sustainability, and user experience of EVs, aligning with global carbon neutrality goals.

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AUTHOR CONTRIBUTIONS

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The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

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