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IMPACT OF THERMAL CONDITIONING ON BATTERY PACK EFFICIENCY AND ASSOCIATED LIFETIME RANGE AND FULLY BURDENED GHG REDUCTION: LITERATURE REVIEW

Final Report

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Impact of Thermal Conditioning on Battery Pack Efficiency and associated Lifetime Range and fully-burdened GHG Reduction

by

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Executive Summary

Electric vehicle (EV) batteries still face significant challenges, such as a) aging at high temperatures that can be avoided by active battery cooling even when parked and b) performance degradation such as limited power availability and charge acceptance in cold temperatures that can be avoided with battery heating. These issues pose a particular hurdle in EV applications, impacting vehicle start-up, shutdown, and the maintenance of thermal conditions even while parked and not actively charging, especially in subzero temperatures.

The cold weather impact on battery performance can be minimized with battery thermal conditioning by a) trickle-heating batteries, or b) by preheating from low temperatures to a pre-specified temperature before vehicle operation. Most methods assume the energy for the preconditioning comes from the grid while the vehicle is plugged in, and a few articles consider draining the stored battery energy to pre-heat if grid energy is not accessible.

The literature presents various preheating methods that have been developed, including convective and conductive heating of individual battery cells or packs, resistance-based heating using thermal jackets, and self-heating through the cell's internal resistance and associated joule heating during the current draw. Since different preheating methods have their pros and cons, it is essential to understand what constitutes effective preheating strategy and quantify the range retention from onboard EV battery thermal conditioning systems or grid systems. The literature focuses on technology development with goals associated with customer satisfaction such as fast warm-up, seamless integration, low-cost implementation, and high-efficiency operation. The efficiency of the various methods is directly affecting the operational cost such as grid-charges or lost range, and is rarely connected with lifetime EV GHG.

Contents

1. Introduction

Lithium-ion batteries have become the epitome of rechargeable technology, benefiting from remarkable advancements in material science over the last decade. These advancements have resulted in increased energy and power density, high efficiency, and relatively long cycle life. Despite the accelerating adoption of EVs, the cold weather performance and the hot-weather battery aging are still under intense research.

The goal of this literature review is to provide comprehensive information about battery thermal conditioning, with a focus on four main aspects: hardware, software, user patterns, and sensitivities to environmental factors. In this study, a comprehensive literature search was conducted using various sources including journals, conference papers, patents, news articles, and blogs to collect relevant publications on the topic of preheating methods and preconditioning for electric vehicles (EVs). Key search terms such as "preheating methods," "preconditioning," and "EV" were utilized to retrieve relevant papers from reputable databases such as Google Scholar, IEEE Explore digital library, Elsevier, and China National Knowledge Infrastructure. Additionally, to gather examples of practical implementation of preheating processes in the industry, sources such as the United States Patent and Trademark Office and the official websites of electric vehicle brands were consulted. These sources provided valuable insights into real-world industrial applications of preheating methods in EVs.

The literature search yielded a total of 110 papers, patents, articles, and blogs that met the inclusion criteria and addressed the topic of interest. Furthermore, through the examination of various EV brand websites, it was found that at least 11 brands have incorporated preheating processes in their electric vehicles. These brands serve as practical examples of the implementation of preheating techniques in the EV industry. These papers, articles and patents were thoroughly reviewed and analyzed to extract relevant information regarding preheating methods, their benefits, limitations, and potential industrial applications. Blogs also serve as a valuable augmentation to our comprehension of preheating technology from an alternate perspective. By tapping into the viewpoints of vehicle owners and electric vehicle enthusiasts, these platforms offer insights into the transformative impact that preheating technology engenders in daily routines. These narratives show the tangible alterations that preheating technology introduces to individuals' everyday lives. Through insights shared through blogs, preheating technology can be improved to better suit users' needs, thus fostering usability and overall user satisfaction.

The remainder of this report is organized as follows: Section 2 elaborates on the preheating methods relevant to automotive applications that are currently being used and explored. It provides details not only about their performance, such as heating rate, but also about the considered battery type, chemistry, geometry, and energy consumption. Section 3 provides a summary of the typical use of preheating methods in the industry based on the information from patents and websites with schematics. Section 4 provides the various views from blogs. Section 5 summarizes the impact of the preheating methods on performance, durability, and environmental effects, facilitating easy comparison. Lastly, Section 6 presents the comparison of those preheating methods and future research trends, concluding with remarks.

2. Preheating methods (Literature review of Journals and Conferences)

Numerous studies have contributed to the development and refinement of preheating techniques in the context of electric vehicles. These techniques can be broadly classified into two categories based on the source of heat: external preheating and internal preheating. The former involves utilizing heat from an external source, while the latter focuses on utilizing heat generated within the battery. Moreover, researchers have explored the possibility of combining external and internal preheating methods to leverage the unique benefits offered by each approach. This hybrid approach aims to optimize the preheating process by harnessing the advantages of both external and internal heat sources. The following diagram visually represents the detailed categorization of these techniques to provide a comprehensive overview of the classification of preheating methods.

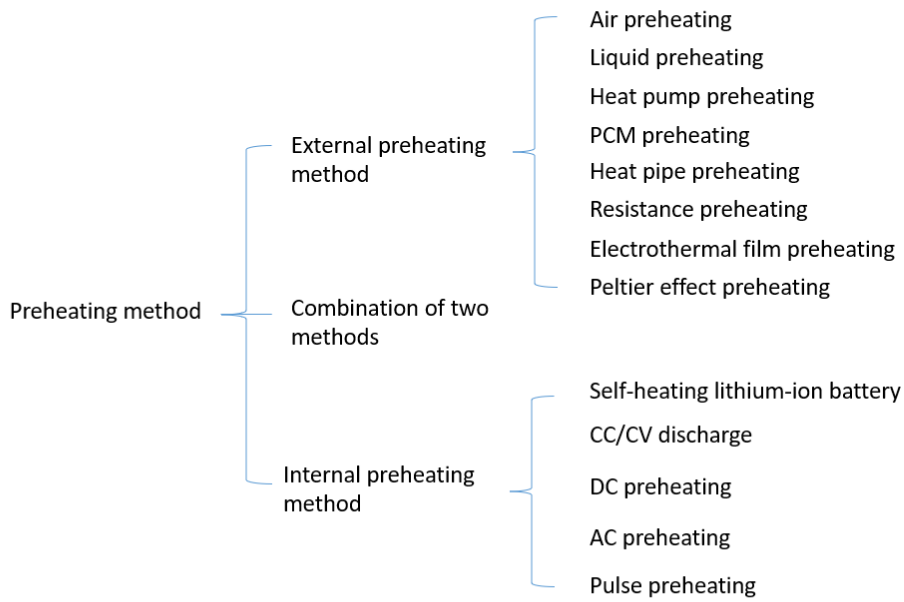


Figure 1 Categorization of preheating methods

2.1 External preheating

External preheating refers to heating the battery from the outside. Many factors affect the external heating performance; in addition to the different forms and structures of the heating method itself, the material, geometry, and materials of the battery will also affect the result of preheating.

2.1.1 Air preheating

In the context of air preheating, the heater used to warm the air can be powered either by an external power source or by the battery itself, as illustrated in Fig. 2. Upon entering the heater chamber, the air undergoes a warming process facilitated by the heater. Subsequently, a fan is employed to blow the warmed air towards the battery chamber, which raises the temperature of the battery through the heat transfer from the warmed air.

The research works presented in [1]-[6] discuss the structure of air preheating, the rate of air preheating, energy consumption, and the impact on the battery's performance and degradation. In [1], the authors constructed a completed model, including a battery system and an air heater as well as and powertrain. They designed the experiment that tested the vehicle in 4 cases to compare performance after preheating. They preheated the battery from -20°C to 25°C at a rate of 0.9°C/min and observed greater mileage induced by preheating. The authors in [2] applied an electrochemical-thermal (ECT) coupled model and powered the heater by the battery itself. After preheating the battery from -20°C to 20°C in 85 seconds with 0.4 Ω heater resistance, the battery capacity loss was about 7%. However, the authors pointed out that this preheating method is not suitable for large-size cells because of the large temperature gradient across the depth of batteries caused by long distances for heat conduction inside cells. In [5], the authors used a PHEV powertrain model where a convective heating function was used to raise the battery temperature from -20°C to 13°C in 714 seconds. With the preheating process, the battery degradation was reduced from 1.647×10^{-4} to 0.336×10^{-4} in which the battery capacity was normalized to 1. Table A.1 provides a summary of papers that have been found using air-preheated batteries. Careful analysis and optimization of this approach are crucial for enhancing the effectiveness of the air preheating system in the context of battery heating applications.

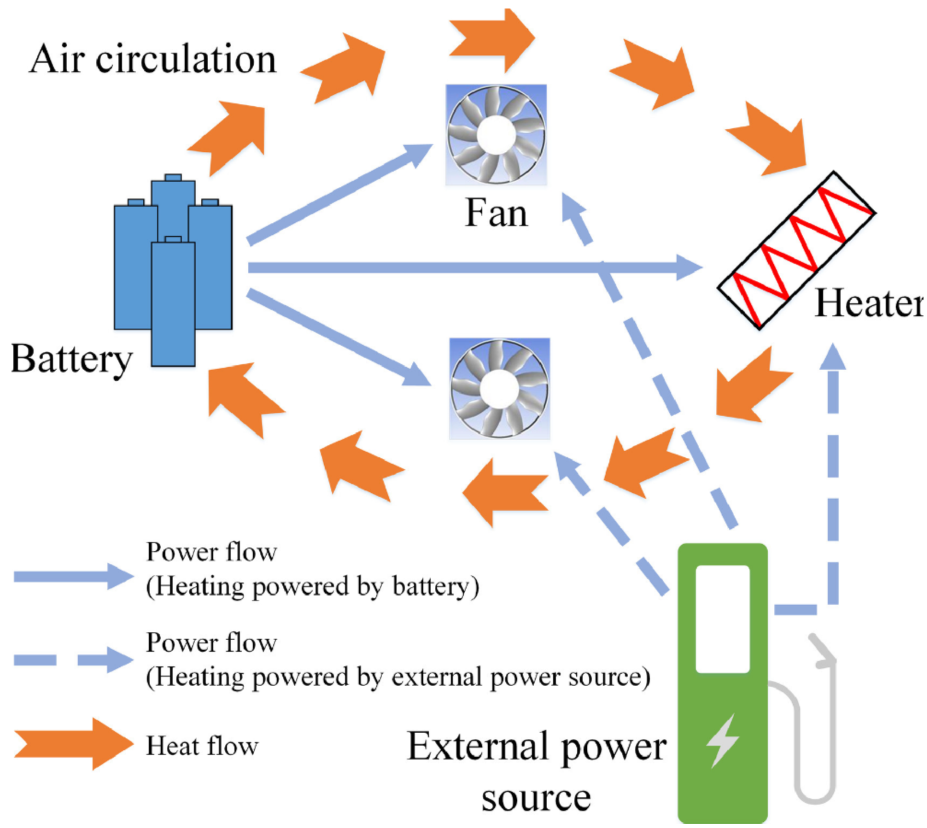


Figure 2 Schematic of air preheating method [7]

Air preheating represents a cost-effective and straightforward solution that can be readily implemented in the electric vehicle (EV) industry. However, this approach may lead to increased noise levels due to fan operation, and it can pose challenges in maintaining consistent temperatures for larger battery cells. Notably, esteemed automotive manufacturers such as Honda and Toyota have successfully incorporated air preheating technology into their vehicles [8][9].

2.1.2 Liquid preheating

Liquid preheating methods can be categorized into two main types: non-contact liquid preheating and immersion liquid preheating. In non-contact liquid preheating, heat is transferred to the battery without direct physical contact between the heating medium and the battery. On the other hand, immersion liquid preheating involves the immersion of the battery in an electrically insulating working fluid to facilitate heat transfer. Figures 3 and 4 illustrate the typical structures of the two types of methods.

Table A.2 summarizes the research work in [10]-[22] where liquid-preheating is used for batteries. In [10], a liquid immersing preheating system was designed using COMSOL. The authors reported a heating rate of 4.18°C/min, and the temperature difference among cells in the pack was under 4°C. On the other hand, the authors in [12] used a double-direction liquid preheating system and reported a higher heating rate of 6.7°C/min and a worse temperature difference of 8.8°C. The authors in [13] conducted a different category of liquid cooling. Three sides and an extra cooling plate were added in the middle of the battery pack to perform the preheating function. They used COMSOL to design their battery heat transfer model and structure model, which was verified by a battery charging experiment, acquiring preheating battery from -

20°C to 15°C in 1740 s and less than 5°C of temperature difference of battery pack when the flow rate of liquid was greater than 0.8 m/s. The research work in [14] reported battery fade ratios with and without preheating: 0.015% and 0.023% in real vehicle testing, respectively.

Some factors could influence the performance of liquid preheating. The choice of heat transfer fluid and its characteristics play a critical role in determining the efficiency of the preheating process. Additionally, the number of batteries being heated simultaneously also affects the rate of preheating [10]. Therefore, the selection of an appropriate heat transfer fluid and careful consideration of the number of batteries are crucial parameters that significantly impact the rate of preheating. In summary, the thermal conductivity, heat capacity, and flow rate of the heat transfer fluid, along with the number and arrangement of the batteries, need to be optimized to ensure efficient and uniform preheating.

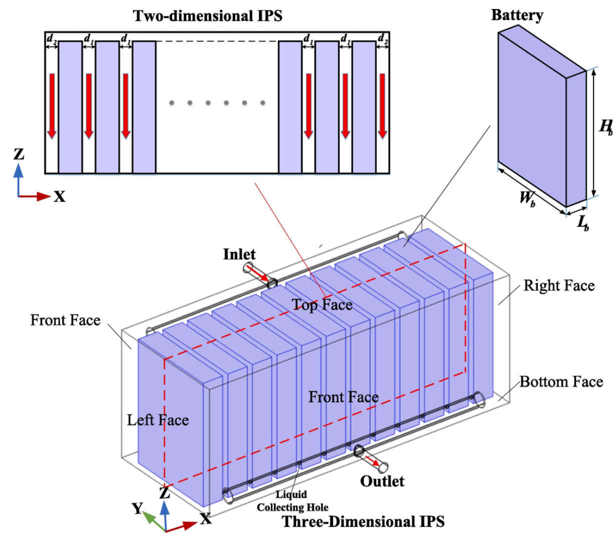


Figure 3 Structure of immersion liquid preheating[10]

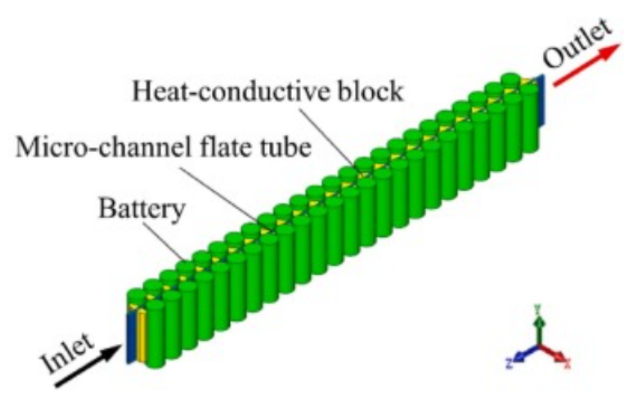


Figure 4 Structure of non-contact liquid preheating [11]

Compared to air preheating, liquid preheating offers a higher temperature rising rate. However, this method requires additional equipment, which can introduce complexity and increase costs. One of the potential drawbacks of liquid preheating is the risk of liquid leakage. Therefore, proper design and implementation measures must be taken to ensure the safety and reliability of the system. Nonetheless, major players in the

EV industry, such as Tesla[23] and Volt[24], have integrated liquid preheating technologies into their products. Xpeng has reported exceptional results in Xpeng G9, achieving a range of up to 702km [25].

2.1.3 Heat pump preheating

The exceptional efficiency of heat pumps can be attributed to their ability to extract heat from the surrounding environment, even at lower temperatures, and transfer it to the desired location. This thermodynamic process enables heat pumps to achieve higher energy efficiency ratios than traditional heating methods. Table A.3 provides a summary of papers that have been found using heat pump preheating methods.

Heat pump preheating can be up to about three or four times more efficient than other forms of heating [26]. The versatility of heat pump technology allows for its application in both cabin and battery heating. However, it is important to note that heat pump preheating may have comparatively slower heating rates, which was 0.3°C/min [27]. Hence, it is predominantly employed for cabin heating purposes rather than rapidly heating a battery pack. Notably, the authors in [28] calculated the emission of CO_2, which was 6g/km, using Audi Q7 as an example. However, this calculation was based on the extending driving range due to the application of a heat pump for cabin heating.

Notably, the heat pump system exhibits remarkable thermal energy generation efficiency, capable of producing 3kW of heat per 1 kW of work. This high efficiency indicates its potential to enhance overall energy utilization and increase driving range in EVs [28][29]. Several automakers, including Tesla, BYD, Hyundai-Kia, and Audi, have included a heat pump system as a part of their battery thermal management systems [30][31][32][33].

2.1.4 PCM preheating

Phase Change Materials (PCMs) are a class of materials known for their capacity to store and release thermal energy through the process of phase change. By leveraging the heat storage capabilities of PCMs, it is feasible to transfer heat to a battery, thereby facilitating its heating. In practice, the battery is integrated and attached to the PCM. This configuration enables efficient heat transfer between the PCM and the battery.

The performance of PCM in preheating applications is influenced by several factors, including cooling, the latent heat capacity of PCM, and thermal conductivity [34]. Table A.4 summarizes the heating rate and differences in battery found from the research works in [35][36] where a PCM preheating method was used. In [35], a device designed for triggering the solidification of the subcooled PCM to release heat to the battery introduced a higher heating rate of 7.5°C/min from 5°C to 20°C compared with 37 mins for the same temperature range with PCM without subcooling. The PCM with subcooling also increased discharge capacity and power up to 9.87% and 7.56%, respectively. The authors in [36] combined the heat sheet with PCM to preheat the batteries. The heat sheet was powered by an external power source and energy consumption was 2000-2500 J/°C. The heating rate was 0.5-1°C/min when the temperature range of the heat sheet was 40°C to 60°C. At the same time, the heat sheet helped to ensure the low temperature difference among cells in the battery model, which was only 2.82°C.

Despite its low cost, simplicity, the absence of the need for additional energy input and the potential to extend battery life [37][38], PCM preheating is currently limited to laboratory experimentation due to several challenges. These challenges include concerns such as increased vehicle weight and low thermal conductivity. Further research and development efforts are required to address these limitations and advance PCM preheating technology beyond its current laboratory stage.

2.1.5 Heat pipe preheating

Heat pipe preheating utilizes the fundamental principles of evaporation and condensation of an internal fluid to facilitate efficient heat transfer. Figure 5 illustrates the structure of heat pipe preheating, providing a visual understanding of its configuration.

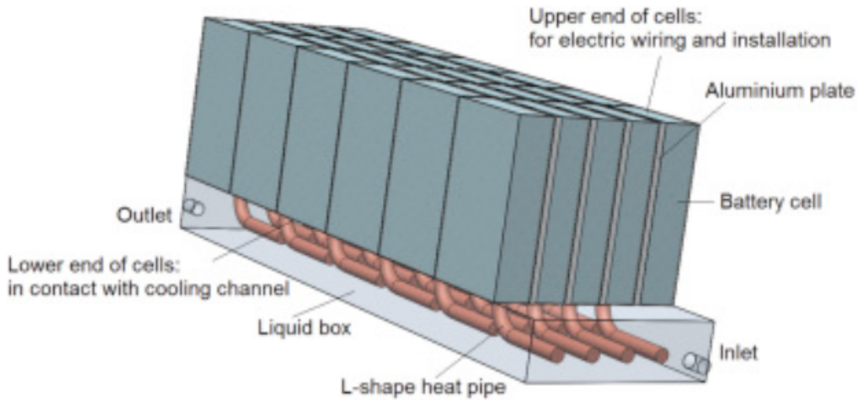


Figure 5 Heat pipe preheating demonstration[39]

Table A.5 summarizes the research works in [39]-[46] where heat pipe preheating is used. The authors in [39] used the external Direct Current (DC) source to power an L-shape heat pipe which was inserted in the cell gap, which realized to heat a battery from -15°C to 0°C in 1200 s with 20°C hot fluid and 300 s with 40°C hot fluid. Notably, the authors in [46] experimented with preheating based on a U-shape Micro heat pipe array (MHPA) and Polyimide (PI) electric heating film on the upper surface of each layer of batteries. Their work showed that the heat pipe may induce higher temperature differences in both battery and module levels. In the battery level, the temperature differences were 1.06°C and 0.97°C with/without a heat pipe, respectively. It was similar in the module level that the temperature differences were 2.35°C and 1.97°C with/without a heat pipe, respectively.

Heat pipe preheating has the potential to integrate both cooling and heating functions, despite their inherent contradictory nature [43][46]. However, during the preheating process, certain prerequisites must be met to initiate the necessary start conditions, ensuring that the coolant temperature reaches a specific predetermined value [40]. It is noted that temperature differences exist along the heat conduction direction of the heat pipe due to its unique structural configuration. These temperature variations may introduce localized thermal inconsistencies that need to be carefully considered and managed in the design and implementation of heat pipe preheating systems [7].

2.1.6 Resistance preheating

Resistance preheating typically utilizes either Positive Temperature Coefficient (PTC) elements or metal resistance elements to generate heat. The energy required for this process can be supplied from an external power source or the battery itself. Figure 6 shows a design of the resistance preheating method, where the PTC resistance band is embedded in the slotted aluminum plates placed between the sides of cells. The heat produced by the PTC elements can be rapidly transferred to the battery, facilitating preheating.

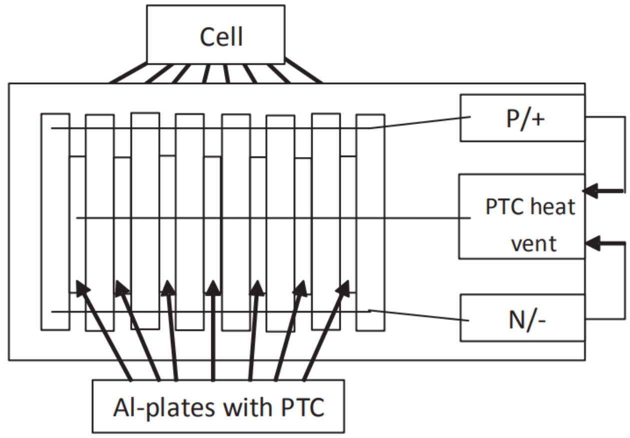


Figure 6 Schematic diagram of a battery-powered resistance heating system [47]

The authors in [48] experimented with PTC resistance preheating in two power cases: external power source and battery as supplying power. The heating rate was 0.504 °C/min. The temperature difference among cells in the pack was 3.506°C in the heating range of -20°C to 0°C. The preheating process consumed about 13% of total pack energy when resistance was powered by batteries. Zhang et al.[49] also reported a temperature difference which was 5.2°C in the situation of the grid as a power source when the PTC was in the bottom of the pack. More details can be found in the summary of the literature [48][49][50] in Table A.6.

Resistance preheating offers advantages over air and liquid preheating, including a shorter heat transfer path and reduced heat loss. While resistance preheating offers a straightforward and cost-effective approach to warming the battery, it is important to note that this method may not be optimal for low initial State-of-Charge (SOC) conditions, when relying solely on battery power. Moreover, the limitations of resistance preheating include its potential negative impact on battery health and its compatibility with certain battery formats.

2.1.7 Electrothermal film preheating

Electrothermal film is an electric heating element that directly converts electrical energy into thermal energy. It can be directly applied onto the surface of each battery cell, facilitating effective heat transfer. As illustrated in Fig. 7, electrothermal films can be connected in parallel inside each battery module.

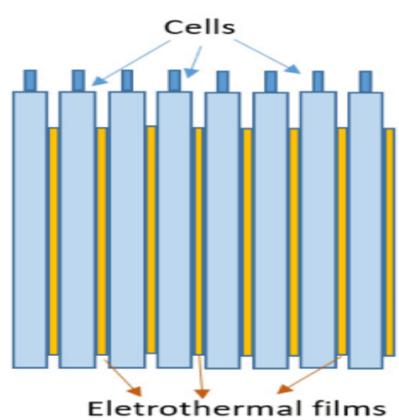


Figure 7 Sketch of a battery module with the cells and Electrothermal film in parallel connection[51]

Table A.7 summarizes the research works in [52]-[55] where electrothermal film was used for preheating. In [52], authors compared a symmetric polyimide (PI) electric heating film and a spiral PI film attached on both sides of the battery with experiments and simulation using an electro-thermal model. Results show that a symmetric PI film has more potential to ensure the uniformity of temperature distribution. However, higher power of heating film can cause increased power consumption and worse temperature differences. In [55], a heating rate of 2.67°C/min was achieved when the wide-line metal film was powered by the battery itself. After preheating, the voltage and power performance of the battery pack was improved at the 1 C rate. The discharging capacity was restored to almost its total room-temperature level and the charging capacity was restored to half its room-temperature level.

Electrothermal film preheating is simple and cost-effective, but the use of electrothermal film may introduce temperature gradients within the battery. The temperature difference between the surface of the battery cell in contact with the film and the internal core of the cell is a noteworthy consideration. These temperature gradients can potentially impact the overall thermal performance and uniformity. Nissan has successfully incorporated electrothermal film preheating into their vehicles [56].

2.1.8 Peltier effect preheating

The Peltier effect is a phenomenon observed when a current flows across the junction of two metals. When the current flows in one direction, heat is absorbed at the junction, and when the current is reversed, heat is liberated. The transition between hot and cold terminals is determined by the direction of the currents applied, and the intensity of the effect is influenced by the amplitude of the current.

In [57], when applying the Peltier effect preheating method on a real vehicle, the heating rate was 1°C/min for the frontal battery box. However, for the rear battery compartment, the heating rate was 0.6°C/min. Due to heat lost to ambient at the hose systems, the temperature difference of 8°C in these two parts was observed. More information can be found in Table A.8.

Peltier-effect preheating offers a simple and cost-effective solution. However, it is important to acknowledge the temperature differences between the region adjacent to the Peltier-effect device and the distant part [57].

2.2 Internal preheating

Internal preheating methods also have demonstrated promising performance in the context of electric vehicle preheating. Several notable approaches have been proposed and investigated, including self-heating lithium-ion batteries, CC/CV discharging, DC preheating, AC preheating, and pulse preheating.

2.2.1 Self-heating lithium-ion battery

This method involves a structural modification of a battery, wherein the battery is securely inserted into a configuration comprising nickel foils with two attached tabs. These nickel foils serve a dual purpose: they generate heat for the battery and act as internal temperature sensors to monitor thermal conditions. Figure 8 illustrates a schematic representation of the newly proposed Self-Heating Lithium-Ion Battery (SHLB) structure.

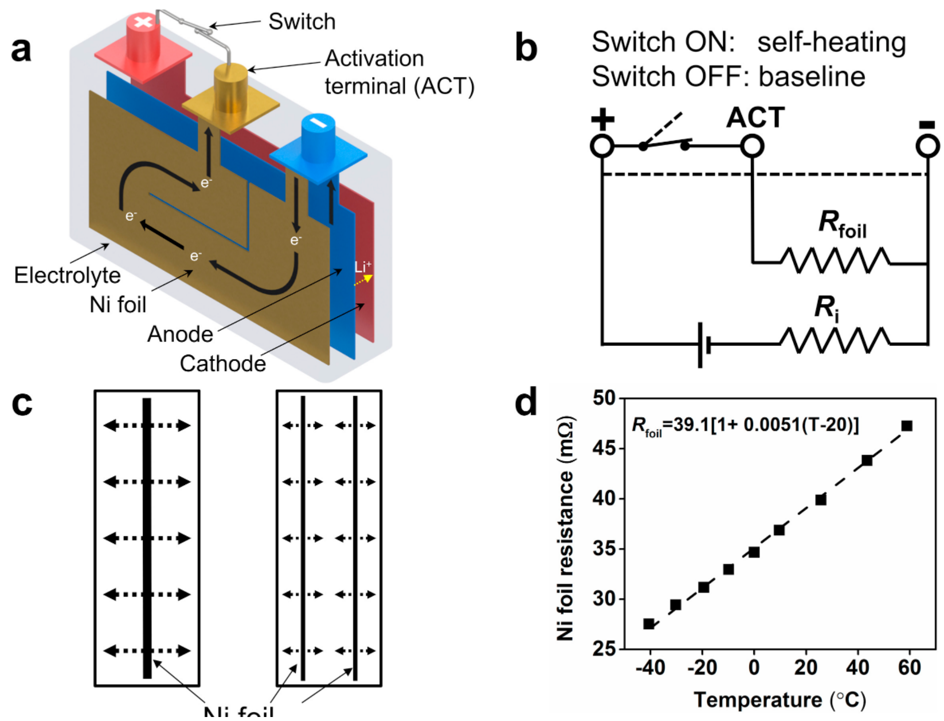


Figure 8 Working principle of rapid self-heating Li-ion battery[58]

Zhang and Wang et al. contributed a lot to self-heating lithium-ion batteries. They inserted two nickel foil sheets in parallel within the 2-sheet cell and preheated the battery from -20°C to 0°C in 12.5s with a capacity consumption of 2.9% [58] compared to one nickel foil sheet in 19.5s with a capacity consumption of 3.8% [59]. They tested the durability of this kind of battery and found that the cell capacity fade was less than 7.2% after preheating at 1 C rate CC-CV charging. A summary of the papers [58]-[64]about preheating methods using self-heating is provided in Table A.9.

The heating efficiency of the self-heating lithium-ion battery is close to 100%. However, temperature gradients are observed across the thickness of a battery cell, which can be addressed by incorporating additional nickel foils within the cell structure. Including nickel foils proves to be an effective solution for mitigating temperature variations. However, determining the optimal number of nickel foils to achieve the desired results remains critical. It is important to note that inserting nickel foils requires modifying the battery structure, which can be costly and risky. Therefore, this approach is currently limited to laboratory testing and cannot be readily applied to existing commercial batteries.

2.2.2 Constant Current / Constant Voltage (CC/CV) discharge

The heat generated in the CC/CV preheating method comes from the internal and polarization resistance. Figure 9 illustrates the voltage, current and temperature evolution during CC/CV discharge.

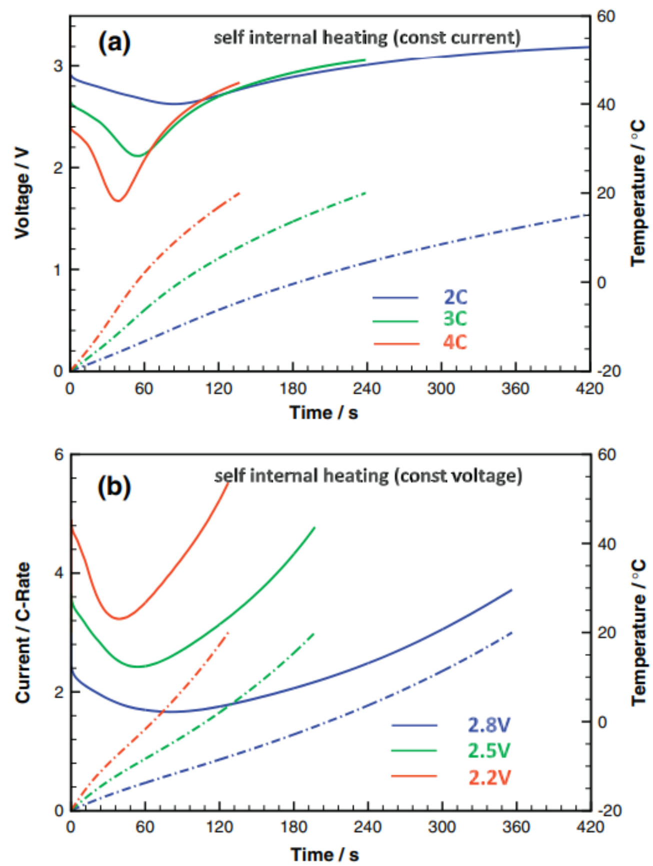


Figure 9 Working principle of rapid self-heating Li-ion battery [2]

CC/CV discharging preheating method does not require an external power supply. However, this method is typically suitable for high SOC situations where the battery has a relatively high energy level. Table A.10 summarizes the heating rate and differences in batteries found in [2][66][67][68] about preheating using CC/CV discharging.

2.2.3 Direct Current (DC) preheating

DC preheating is a method employed to warm the battery using direct current (DC) electrical energy. This direct transfer of electrical energy into heat enables efficient conversion and utilization of the energy input, resulting in a high temperature rising rate. Figure 10 illustrates the temperature evolution, heating power, current and voltage of the battery, and capacity loss when applying DC preheating.

As summarized in Table A.11, compared to other preheating methods, DC preheating offers notable advantages, including a high rate of temperature rise which is 18.67°C/min from -30°C to 2.1°C[69] and ease of implementation[70]. However, one of the potential drawbacks associated with this method is the risk of lithium precipitation [70], which can result in reduced battery capacity and safety concerns. The authors in [70] showed that the state of health (SOH) dropped to 0.7 at 81st preheating cycle due to cracks in the electrode material caused by lower discharge voltage and higher polarization in DC preheating. Consequently, heating the electrolyte with DC currents is considered impractical and excessive gassing may occur before significant heating is achieved.

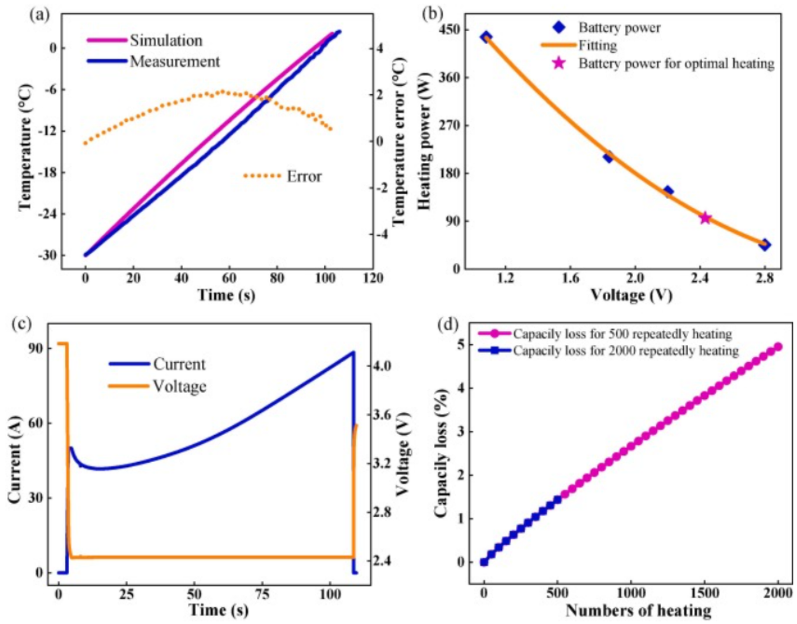


Figure 10 Heating results of DC preheating[69]

2.2.4 Alternating Current (AC) preheating

AC preheating involves using alternating current (AC) electrical energy to heat a battery. Fig.11 provides the AC curve profile and battery temperature evolution. A summary of the research works in [71]-[83] that have been found using AC preheating is provided in Table A.12. The heating rate dropped in the range of 1-13.33°C and the temperature difference among cells in the pack dropped in the range of 0.3-2.9°C.

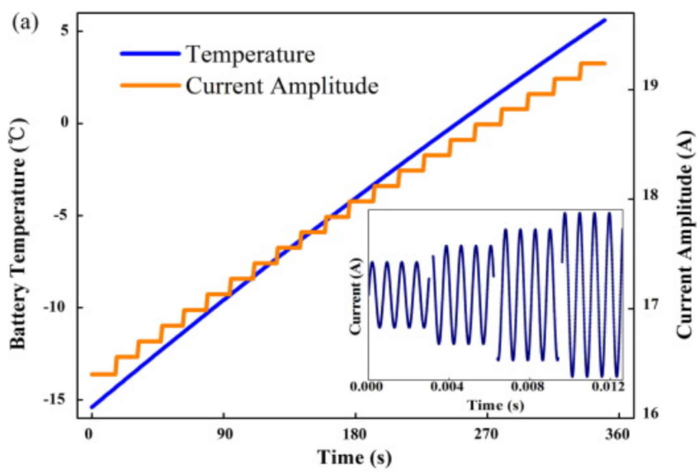


Figure 11 Heating simulation results with constant frequency and variable amplitude of sinusoidal AC (SAC)[75]

AC preheating presents advantages over DC preheating in terms of battery health and voltage protection. The research works in [74]- [77] showed that irreversible damage to a battery and obvious an detrimental effect on the battery health was not observed when applying AC, even in the low frequency range. By imposing limitations on the amplitude and frequency of the AC signal, it is possible to ensure that the voltage remains within safe operating conditions. Furthermore, the heating circuit required for AC preheating is simple, although it often necessitates external power sources. The development of onboard devices that enable AC preheating without the need for external power supplies would enhance the practicality and autonomy of AC preheating systems, facilitating their widespread implementation in battery heating applications.

2.2.5 Pulse preheating

Pulse preheating is a method employed to warm a battery by applying short pulses of electrical energy to warm a battery, as shown in Fig. 12.

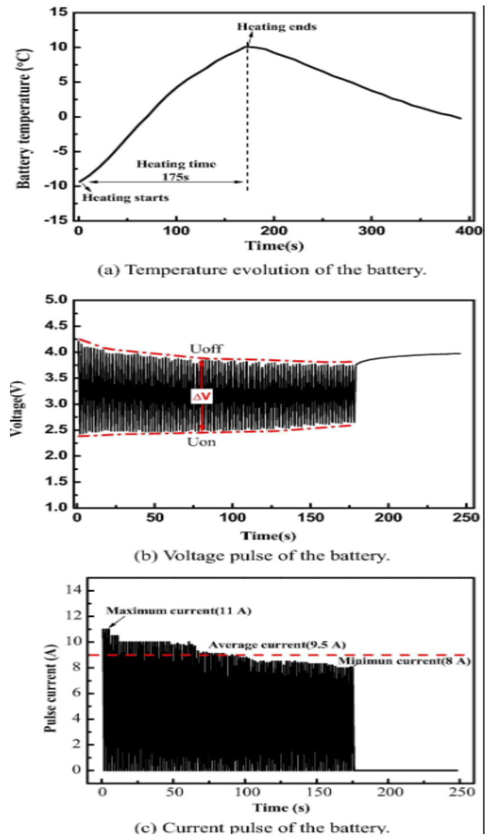


Figure 12 Heating results with pulse currents [70]

Pulse preheating offers the advantage of causing low damage to the battery during the heating process. The authors in [84] showed that the battery only had a capacity loss of 0.035% after 30 heating cycles from -20°C to 5°C. In [85], it was reported that after 10 preheating cycles, the initial capacity of the cell was changed by only 0.4%. However, implementing pulse preheating can also introduce challenges related to complex equipment and cost. Table A.13 summarizes the research works in [84]-[89] where pulse preheating is used.

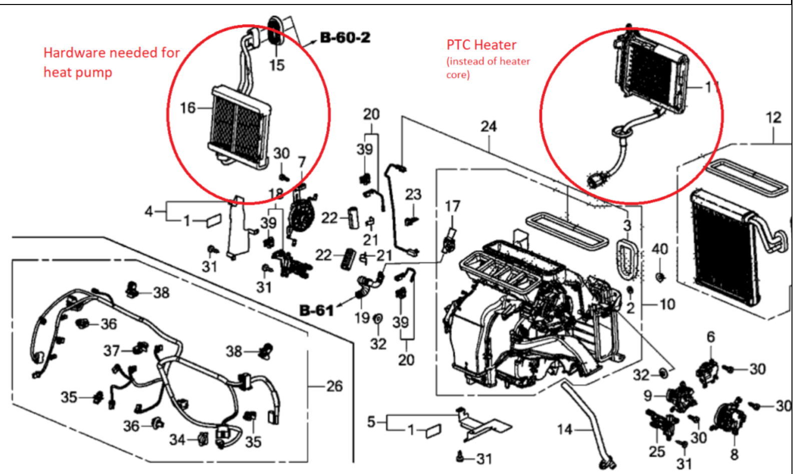
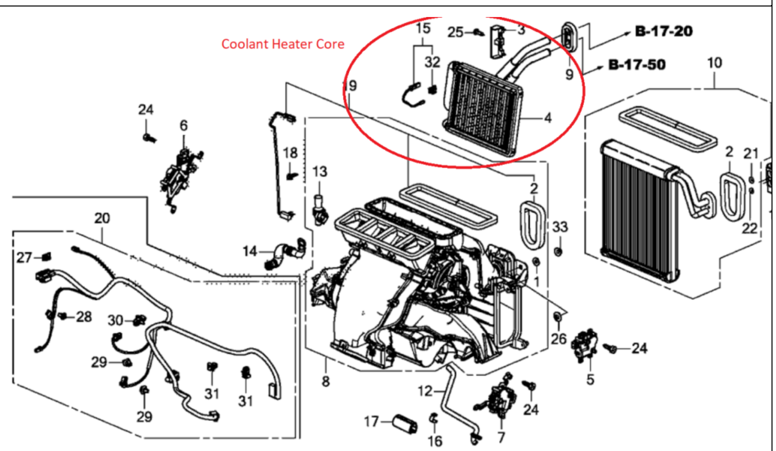
2.3 Combination of external and internal preheating

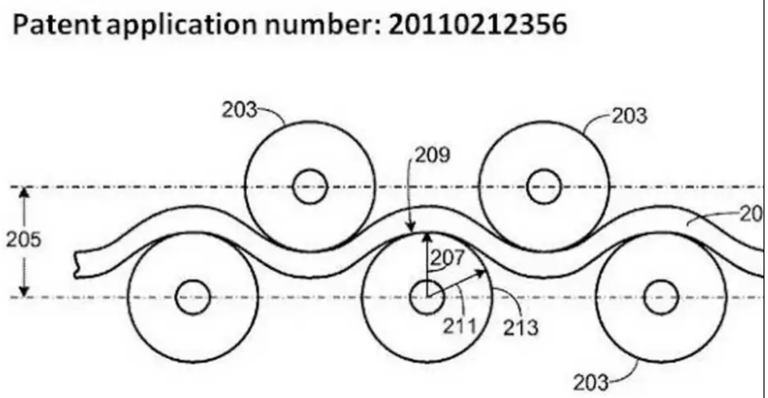
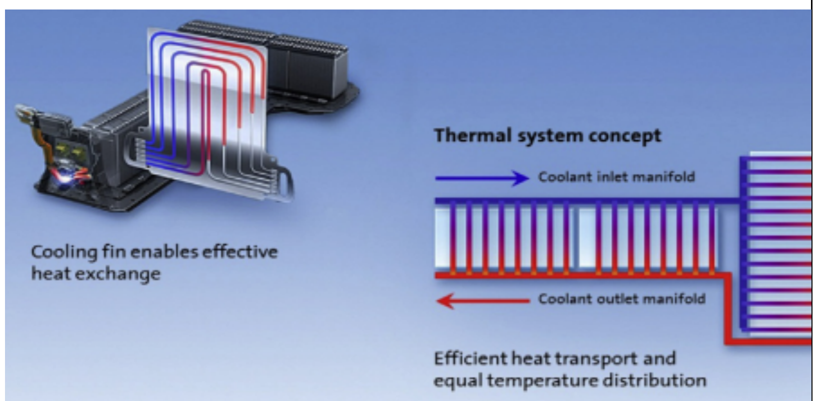
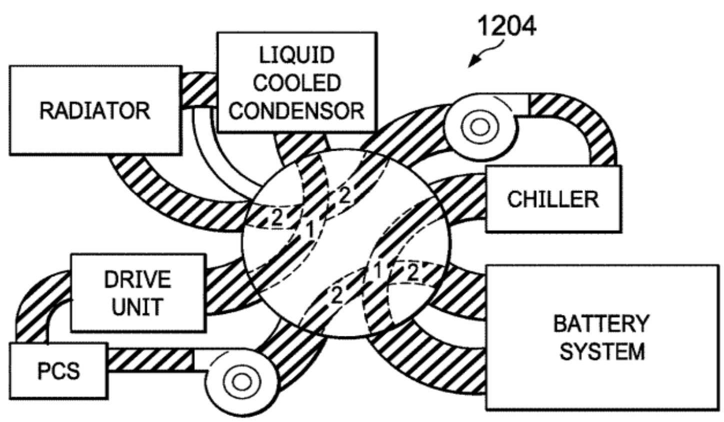
The combination of internal preheating and external preheating represents a promising approach in the field of battery heating. This method leverages the benefits of both internal and external heat sources to achieve a more effective and efficient battery heating process. Furthermore, this method can lead to higher temperature rising rates with a range of 0.352°C/min to 16°C/min and more uniform temperature distributions. Table A.14 summarizes the heating rate and differences in battery found from [47][90][91][92] about the method combining external and internal preheating methods.

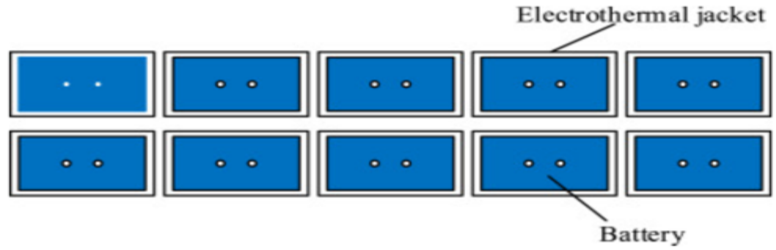
3 Industry applications of preheating including Patents and Websites

Electric vehicles (EVs) experience a drop in range and longer charging times during winter conditions [93]. Preheating plays a significant role in enhancing the winter driving range of EVs, and its implementation has been successfully achieved in the automotive industry. Investigating the specific requirements, challenges, and outcomes of preheating in industrial applications and exploring the utilization of preheating methods in the industry offer valuable insights that can contribute to the improvement of preheating techniques tailored for real-world EV applications, thereby enhancing the overall performance of EVs. The following are typical applications of preheating methods utilized in EVs.

Table 1 Summary of specific applications of preheating methods in electric vehicles

Heating method in industry application	Source (patents, blog, website)	Schematics
Air preheating in Honda Clarity BEV and Toyota: PTC heater for air preheating	[8]https://carswithplugs.com/2018/03/17/electric-car-heaters-honda-clarity/ [9] Battery usage and thermal performance of the Toyota Prius and Honda Insight during chassis dynamometer testing. In Seventeenth Annual Battery Conference on Applications and Advances,2002. https://doi.org/10.1109/BCAA.2002.986408	
Liquid Preheating Honda Clarity PHEV: The heater will heat the coolant and flow it through the heater core in the cabin	[8]https://carswithplugs.com/2018/03/17/electric-car-heaters-honda-clarity/	
Liquid Preheating in Tesla and GM: The preheating system is based on a ribbon shaped metallic	[23]Tesla or GM: Who Has The Best Battery Thermal Management? (insideevs.com)	

cooling tube that snakes through the battery pack		
Liquid Preheating in Volt: Containing a fluid heater to keep the battery temperature above the outside temperatures in cold climates	[24]The Voltec System—Energy Storage and Electric Propulsion. In Lithium-Ion Batteries,2014 https://doi.org/10.1016/B978-0-444-59513-3.00008-X	
Heat pump preheating in Tesla, BYD, Hyundai and Audi	[30]Optimal source electric vehicle heat pump with extreme temperature heating capability and efficient thermal preconditioning. U.S. Patent, 2021 https://insideevs.com/news/452464/tesla-model-y-heat-pump-system-details/ https://teslaownersonline.com/attachments/tesla-heat-pump-patent-pdf.34276/ [31]https://pushevs.com/2021/09/20/introducing-the-latest-byd-e-platform-3-0/ [32]https://www.evspecifications.com/en/news/fcd02e7 [33]https://www.audi-mediacenter.com/en/emotive-design-and-revolutionary-technologythe-audi-e-tron-gt-quattro-and-the-audi-rs-e-tron-gt-13655/battery-and-thermal-management-13784	
Resistance Preheating in Nissan LEAF and Mitsubishi i-MiEV The main cabin heater systems employed electrical resistive heating	[56]Winter happens: The effect of ambient temperature on the travel range of electric vehicles. IEEE Transactions on Vehicular Technology, 2016 https://doi.org/10.1109/TVT.2016.2544178	N/A

Electrothermal jackets in Chery Auto: A resistive heater wraps around each battery cell; restore the battery to the normal working temperature range in about ten minutes with uniform temperature distribution.	[94]The state of the art on preheating lithium-ion batteries in cold weather. Journal of Energy Storage, 2020 https://doi.org/10.1016/j.est.2019.101059	
Pulse preheating in Changan Auto High-frequency pulse heating technology with alternating current	[95]https://fuelcellsworks.com/news/chinas-first-mass-produced-hydrogen-electric-vehicle-comes-from-changan-dark-blue/	N/A

4. Review of opinions expressed in publicly accessible blog

For a comprehensive review of the electric vehicle preheating process, we have not only reviewed academic papers, official websites, and patents but also extensively gathered insights from blogs and forums. By incorporating information from these blogs and forums, we aim to capture diverse opinions and experiences related to preheating methods for electric vehicles. These sources provide valuable insights into real-world scenarios, user feedback, and practical challenges encountered during preheating implementation, complementing the findings from academic and industrial research.

4.1 Comparison of 13 popular EV models on winter range loss [96][97]

Recurrent conducted a comprehensive data collection encompassing 7000 vehicles, representing 13 distinct EV models. This work aimed to comprehensively examine the performance of EVs under winter conditions. The factors influencing winter range include all real-world variables, such as uneven terrain, variable driving speeds and patterns, and calendar aging in vehicle batteries. However, a comparative analysis of range reduction still offers insights into the diverse strategies employed by distinct EV models to confront cold weather conditions.

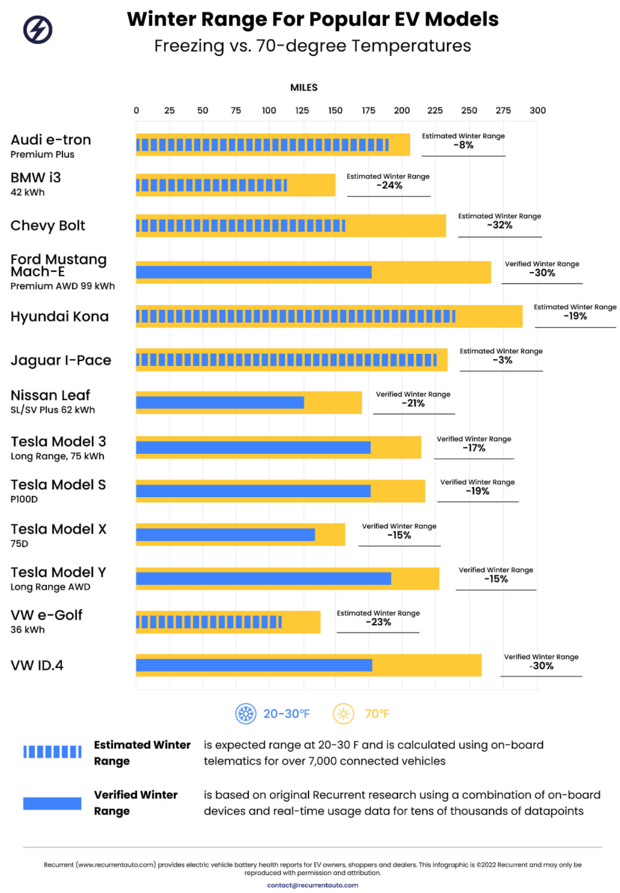


Figure 13 Winter range for 13 popular EV models

Presented in Fig. 13, *Recurrent*'s findings outline the winter driving mileage of the 13 EV models. Among these models, the Audi e-tron serves as a notable example, showcasing a mere 8% reduction in driving mileage. This performance can be attributed to the e-tron's innovative heat pump system, a mechanism for interior cabin heating without undue depletion of the high-voltage battery. Additionally, this system harnesses the capacity to recover and channel up to 3 kW of waste heat generated by the vehicle's motor. Similarly, Jaguar I-pace has demonstrated a 3% estimated loss owing to its heat pump system. Tesla has also integrated a heat pump system into their preconditioning technologies. With a more sophisticated heat pump system to help control battery temperature, Tesla Model X and Y only experienced a 15% reduction in verified range during freezing temperatures. In contrast, the Tesla Model 3, which utilizes waste heat from its motor to warm the battery, exhibited a relatively higher range loss of 17%. Volkswagen ID.4, despite featuring remote preconditioning functionality, experienced a substantial 30% loss in driving range. Notably, the deployment of preconditioning in conjunction with a resistive cabin heater in Volkswagen ID.4 resulted in a discernible drain from battery power.

This comparison of *Recurrent* underscores the significance of effective thermal management systems, especially heat pumps, in guaranteeing optimal electric vehicle performance during winter conditions. The varying outcomes across different models emphasize the importance of selecting and designing appropriate preconditioning technologies to enhance overall performance in cold climates.

4.2 Charging test 2022 in winter conditions by NAF[98]

In 2022, the *Norwegian Automobile Federation* (NAF) conducted a comprehensive test, presenting an overview of the charging characteristics, maximum power, and charging speed of 31 EVs during winter conditions. Moreover, NAF provided calculations of the driving range for each vehicle after 25 minutes of charging in winter conditions. Notably, this year's test revealed that several electric cars now offer the option of preheating the battery before fast charging, a technology previously limited to Tesla and Porsche models. Other EV brands, such as the Audi e-tron GT, BMW i4 M50, Mercedes Benz EQS, Polestar 2 LR Single Motor, and Volvo C40 Recharge, have also integrated this smart function into their vehicles.

The test results demonstrated the substantial advantages of preheating the battery prior to fast charging, particularly in low temperatures, in ensuring rapid charging. The Porsche Taycan 4 Cross Turimos and the Audi e-tron GT emerged as the top performers in terms of the fastest charging under winter conditions. These vehicles managed to charge from 4% to 80% capacity in approximately 20 minutes, as shown in Fig.14.

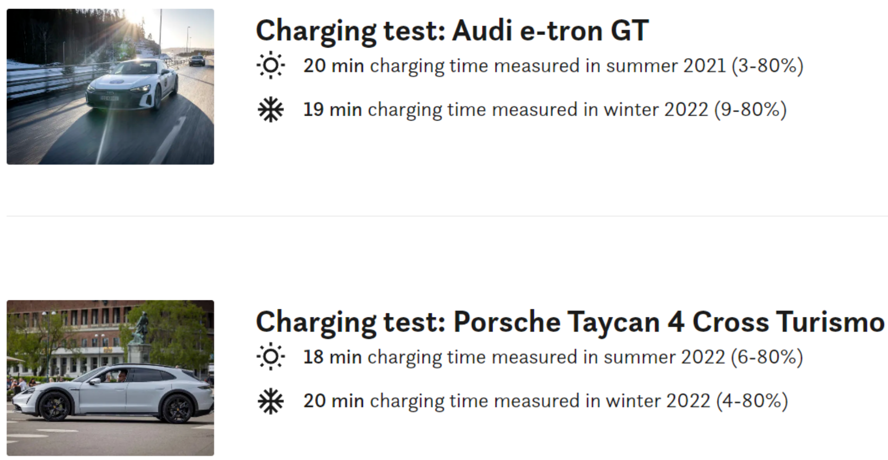


Figure 14 Test results of Porsche Taycan 4 and Audi e-tron GT

This test also calculated the driving distance achievable after charging for 25 minutes. The Tesla Model 3 Long Range yielded a result of 368 kilometers from a 25-minute charging session, securing the top position. In second place came the Mercedes Benz EQS, with a range of 343 kilometers, which can be seen in Fig. 15.

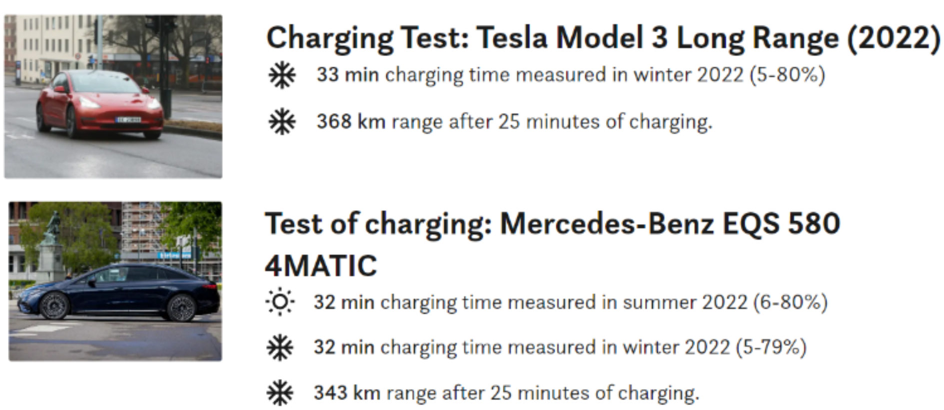


Figure 15 Test results of Tesla Model 3 and Mercedes-Benz EQS

As the EV market continues to evolve, the integration of preheating technology into more vehicle models is expected to further advance charging capabilities and bolster the overall performance and user experience of electric vehicles during the winter season.

4.3 User experience discussion on battery preheating in some EV brand forums

In addition to the test results, discussions among EV owners in the forum on battery preconditioning are worth paying attention to. These discussions are mainly about the necessity and practical benefits, as well as the energy expenditure and sources of thermal preconditioning.

4.3.1 Chevy Bolt EV Forum [99]

The Chevy owner community engaged in a discussion regarding the necessity of battery preheating, highlighting considerations of this function’s energy efficiency and practical impact. Owner *PLP* posited that preheating batteries is wasting energy and is inconsequential, primarily due to the argument that the battery's temperature would inevitably return to ambient conditions once the vehicle is exposed to its surroundings. However, owner *Arob* had an alternative viewpoint. *Arob* extensively used battery preconditioning on cold mornings to drive comfortably. Other owners also emphasized that warming up the battery before driving off would contribute to an extended driving range, although disregarding the expense of additional energy consumption.

4.3.2 Tesla Motor Club[100]

Tesla owners shared their insights on the value of preconditioning before fast charging. They reached a consensus that preconditioning plays a pivotal role in the supercharging processes, despite its significance being contingent upon temperature conditions. Member *avs007* introduced the concept of “cold gating”, which can impede fast charging in cold conditions. Following the implementation of preconditioning and the temperature of the battery rising above 35 °C, Tesla Model 3 exhibited the highest charging speeds during Bjorn's testing. However, some individuals also pointed out that if monetary considerations outweigh time concerns, it is a judicious choice to avoid thermal preconditioning before charging due to the energy consumption associated with the preconditioning process. Member *STS-143* introduced another perspective on the essentiality of thermal preconditioning to prevent detrimental effects on battery lifespan. Their perspective underlined the potential formation of dendrites and other undesirable anomalies if batteries undergo rapid charging at low temperatures.

4.3.3 Kia EV Forum[101]

Certain Kia EV models have been equipped with battery preconditioning functionality. To understand the working principles and the influence of preconditioning, and to substantiate a conjecture that battery preconditioning works more effectively without cabin preconditioning, *Alexw* conducted a road trip test. Following the requirements of preconditioning to start outlined in Kia’s document[102], the battery preconditioning function is selectively engaged when the battery's temperature hovers beneath 21 °C, and the State of Charge (SOC) of batteries surpasses 24%. Therefore, *Alexw* chose the mild temperature conditions to lower the battery temperature to 13 °C and then compared the preheating rate with/without cabin preconditioning. The outcomes revealed that it took approximately 25 minutes to preheat the battery from 14 °C to 23 °C, irrespective of cabin preconditioning activation. However, a divergence happened in energy consumption. The scenario involving cabin preconditioning recorded a higher energy consumption of 2.4 kWh, compared to the 1.6 kWh consumed in its absence. This difference stemmed from the operation of the heat pump system, which would consume the energy of batteries.

4.3.4 BMW i4 Forum [103]

BMW i4 community engaged in a discussion concerning the energy source for battery preconditioning. *Mikeyf79* thought preconditioning is designed to draw power from an external power source, such as a wall socket, especially when the SOC of high voltage batteries is low. According to the information found in BMW USA News[104], BMWi4 has been equipped with a heat pump system that is assisted by a pair of powerful continuous-flow heaters, each capable of delivering 9 kW of heating power. A query arose within the owner community regarding the adequacy of power sourced from level 2 charging stations to effectively meet the energy requirements for preconditioning, suggesting that under specific circumstances, the high voltage batteries might indeed participate in the preconditioning process. However, the associated capacity consumption of the battery would be negligible, which was proved by the experience of certain owners.

4.4 Observation of energy consumption of preheating in Tesla

Addressing the energy consumption associated with battery heating becomes critical for automakers and charging infrastructure providers. This is also why we have included information about the energy consumption of various preheating methods from the reviewed papers. By adopting more energy-efficient heating methods and optimizing heating processes, the industry can mitigate the financial burden on users and improve the overall charging experience.

4.4.1 Tesla Model 3 charging losses in Tom Moloughney's blog[105]

Tom's observation regarding the discrepancy in the amount of electricity charged between the in-car screen and the charging station screen during the charging process of his 2021 Tesla Model 3 in New Jersey raises pertinent concerns regarding charging efficiency and potential charging losses. Subsequent analysis by Tom indicates that the thermal management system, designed to optimize battery performance during DC fast charging through preheating or cooling, appears to be a primary contributor to charging losses, whereby a portion of the energy intended for charging the battery is diverted for heating or cooling purposes.

4.4.2 Heating the battery until 55 °C before and during the DC charging in Tesla Motors Club[106]

The blogger's analysis highlights a critical observation regarding the energy consumption attributed to battery heating, amounting to 4 kW. This persistent heating practice leads to an additional 10% tax on the energy bill for users, indicating a potential financial burden for EV owners. Notably, the continuous battery heating appears to contribute to the discrepancy observed between supercharger billing and in-car billing, as previously discussed by Tom Moloughney.

5 Summary table of all preheating methods

A comprehensive analysis of various preheating methods from the extensive collection of papers, articles, patents and blogs has been conducted, identifying their respective advantages and disadvantages. Furthermore, the impact of preheating methods on battery performance, including factors such as efficiency, charging time, and overall battery health, has been meticulously examined. In parallel, the environmental implications of preheating methods have been considered, with a focus on their potential effects on greenhouse gas emissions and overall sustainability. Finally, the practical application of preheating methods in the industrial sector has been included.

Based on the comprehensive analysis and review of the collected papers, it is evident that the preheating process holds significant potential to enhance the driving range of vehicles operating in cold climates while simultaneously reducing charging time. Through the meticulous adjustment of preheating parameters and optimization of the preheating method's structure, coupled with the exploration of advanced control algorithms, a rational preheating process can be achieved, resulting in improved battery performance and reduced degradation rates.

However, it is worth noting that the existing degradation models predominantly employed in the analyzed papers are primarily empirical in nature. These models lack a comprehensive understanding of the underlying physical processes such as lithium plating and solid electrolyte interphase (SEI) growth. The incorporation of these physical phenomena into degradation models is an area that warrants further research and development.

Furthermore, the current literature provides limited insight into the environmental benefits of preheating processes in terms of greenhouse gas emissions. While the advantages of preheating methods for driving distance and charging time have been extensively explored, the potential positive impact on reducing greenhouse gas emissions has not been extensively addressed in the reviewed papers. Therefore, future studies should consider evaluating the environmental implications and quantifying the potential reduction in greenhouse gas emissions associated with the implementation of preheating processes.

In conclusion, the findings from the collected papers emphasize the potential of the preheating process in enhancing driving range and reducing charging time. However, further research is required to develop physically based degradation models and comprehensively assess the environmental benefits of preheating methods in terms of greenhouse gas emissions. This will contribute to the advancement and optimization of preheating techniques, ensuring improved battery performance, reduced degradation rates, and a more sustainable approach to electric vehicle operation.

Table 2 Summary of advantages and drawbacks and impact of battery in all preheating methods

Heating method		Advantages	Drawbacks	Impact			Application (EVs patents)
				Performance (Charging time, range, discharge power, regen, efficiency)	Durability (Cap/Power fade rate)	Environment (Scope 1,2,3 and GHG emissions)	
External Preheating	Air preheating	1. Cost effective 2. Simple	1. Noise 2. Temp inconsistent (Large cells)	1. Greater mileage [1]	1. Air Higher velocity of air →bigger temp gradients, harmful to battery life [3]	N/A	1.Honda Clarity BEV (PTC heater for air preheating) 2.Toyota
	Liquid preheating	1.Higher rate compared with air preheating	1.More complex 2.Higher cost 3.Risk of liquid leakage	1.Xpeng G9 has achieved a range of up to 702 km[25]	2.The battery fade ratio is 0.015% in experiment.[14]	N/A	1. Honda Clarity PHEV (coolant-based heater) 2.Tesla (based on a ribbon shaped metallic cooling tube) 3.Volt (fluid heater) 4.GM (2 KW heater will heat coolant and the rate is 0.5 °C/min) 5.Xpeng (the waste heat of the motor and the PTC heater are used to heat the antifreeze)
	Heat Pump preheating	1.Efficient	1.Add cost and complexity. 2.Cause noise. 3.Slow	1. Heat pump can recover 20% of cold-weather range loss. 2. power consumed on	N/A	1.For the Audi Q7 e-tron with a heat pump system for cabin	1.Tesla 2.BYD 3.Hyundai 4. Audi

			4.Tesla's design: depletion of refrigerant.	heat pump preheating <38.4% than the PTC[27]. 4.For the Audi Q7 e-tron using an integrated heat pump results in an average increase in electric driving range of more than 10% [28].		heating, the CO2 is 6g/km.[28]	
	PCM preheating	1. Low cost and less complex 2.No additional energy	1.Low thermal conductivity 2.Increase in mass of the vehicle	1.The maximum increase in discharge capacity and power up to 9.87% and 7.56% in the PCM with subcooling used increased local pressure[35]	N/A	N/A	1.In the laboratory stage 2.A patent of ZEVX reports plant-based PCM
	Heat pipe preheating	1.Low cost 2.Light 3.Good heat transfer performance 4.Realization of integrating the cooling and heating functions.[46] (but have a negative impact on each other)	1.Limited application due to the shape of battery. 2.Temperature difference exists along the heat conduction direction of the heat pipe. 3. Coolant temperature should go to some certain value, which means that it has necessary start condition [40]	1.After heating at the ambient temperature at -10, -20 and -30°C, discharge voltage increased to 3.06V, 3.01V and 2.99V, while the discharge capacity increased by 3.9%,11.6% and 24.4% respectively.[42]	N/A	N/A	N/A
	Resistance preheating	1.Shorter heat transfer path and less heat loss compared with air and liquid	1.Bad for low SOC initial states 2.Limitation in format of battery	1.After heating, discharge capacity at 0.3C from 21.9 Ah increases to 24.11 Ah.[50]	N/A	N/A	1.Nissan LEAF 2.Mitsubishi i-MiEV
	Electrothermal film preheating	1.Simple and low cost	1.Restricted application scenario 2.Temp gradient (surface to internal sore)	1. The voltage and power performance of the battery pack were improved (1C), and the discharging and charging capacity were restored almost to total and half	N/A	N/A	1.Cherry Auto

				its room-temperature level [55].			
	Peltier-effect preheating	1.Simple and low cost	1.Tempeature difference between the part near Peltier-effect device and the part not near it	N/A	N/A	N/A	N/A
Internal preheating	Self-heating Lithium-ion battery	1.Heating efficiency close to 100%.	1.Temperature gradients in the thickness of the cell (add more nickel foils to solve it)[58]. 2. Requiring modification of battery structure. which is costly and risky. 3. Only tested in the lab and cannot be applied to existing commercial batteries.	1.The self-heated all climate battery cell yields a discharge/ regeneration power of 1061/1425 w/kg at 50% SOC in the ambient temp of -30 °C[59].	1.After 500 preheating at CCCV (1C), the cell capacity fade is less than 7.2%[59]. 2.SHLB can achieve 500 cycles in 3C fast charging at -30 °C, while the conventional cells would lose 20% capacity after 12 cycles[60].	N/A	N/A
	CC discharge/ CV discharge	1.No need external power supply 2.Low cost	1.Only for high SOC 2.low heat transfer efficiency	1.Charging capacity can reach 85.32% to 1.169 Ah at -10°C and the charging time is decreased with multistage CC-CV strategy.[66]	1.multi-objective optimization self-heating method can decrease the capacity fade by 5.65% and the power consumption by 3.04% compared with CC discharging.[67]	N/A	N/A
	DC preheating	1.High rate 2.Simple	1.Lithium precipitation 2.decaying capacity 3.Damage to safety	1.The heated battery can offer 8.7/32.7 times the discharge/charge power and 62.46 times the discharge energy of the unheated battery.[69] 2.The heating efficiency is 15.3%[70]	1.The capacity loss is only 1.4% after 500 repeatedly heating.[69] 2.The SOH in DC heating drops to 0.8 at the 81st cycle. The lower discharge voltage and higher polarization in DC heating easily cause cracks in the electrode material[70]	N/A	N/A
	AC preheating	1. Heating circuit is simple	1.Need external power sources	1. AC can increase the resistance from 1.36 Ohm in -30°C to 0.205 Ohm in 25°C, which makes battery deliver more power. [71]	1. Capacity loss is not seen after repeated preheating experiments [74] 2.After heating 30 times, IC peak are almost the same, which means there is no obvious detrimental effect	N/A	N/A

				2.At both -20 °C and -30 °C, 10-20 kHz AC currents at 60-80 Arms can restore the battery resistance to values close to that at 25 °C[72].	on the SOH of LIBs[75]. 3.After 20 and 40 times heating (rectangular pulse-1Hz-10A), 3.7% and 6.6% capacity fading are observed, and DC resistance increases by 1.2% and 2.2% respectively. When the frequency exceeds 10 Hz, the capacity and impedance would barely experience any attenuation[76]. 4.The AC preheating does not cause irreversible damage to the battery even in the low frequency range (0.5 Hz) under normal voltage protection limitations for the battery [77]. 5.After heating 40 times, there is no obvious capacity deterioration[78]. 5. The AC frequency should be as high as possible without detrimental effect[81].		
	Pulse preheating	1.low damage to battery 2.Decrease capacity loss, compared with AC and DC preheating methods.	1.Add more complex equipment. 2.Add cost	N/A	1.The SOH in pulse heating drops to 0.8 at 180^{th} cycle[70]. 2. The battery only had a capacity loss of 0.035% after 30 heating cycles[84]. 3.After 10 preheating cycles, the initial capacity of the cell is changed by only 0.4% [85].	N/A	1.Changan Auto (high-frequency pulse heating technology with alternating currents and heating speed is 4 °C/min)
Combination of external and internal preheating method	1.Discharge heating + PTC 2.Air preheating + Internal preheating (CV-CC-rest phase) 3.Electrothermal film preheating + AC	1. Temperature uniformity 2. High temperature rising rate	1. Add complexity and cost	N/A	1.After preheated to 0.5 °C, battery pack can discharge for 10s at 3C pulse current, but not at the 3.5C[47].	N/A	N/A

6 Comparisons and Conclusions

The preheating methods are evaluated and compared across five key dimensions, including heating rate, temperature difference (temperature uniformity), (less)capacity consumption, degradation rate (battery health) and less cost, employing a radar map and a bar chart to illustrate the results.

6.1 Comparison methodology for bar chart

We represent the maximum and minimum values of each preheating method for each indicator in a bar chart based on the papers in the collection. This bar chart helps to visually depict the properties of each preheating method. In the process of evaluating preheating methods using the bar chart, we have normalized the data for each index. After normalizing the values, the maximum and minimum values for each preheating method in a particular index from all the reviewed papers can be properly compared. However, it is important to acknowledge that limitations in data availability may impact the completeness of the bar chart. In some cases, they may be missing or unavailable information for a specific preheating method under a particular indicator. For example, the case of air preheating lacks information about temperature differences. We have made efforts to collect comprehensive and reliable data for all indicators and preheating methods to ensure the accuracy and completeness of the evaluation. The evaluation results are reflected in Fig. 16. It is worth noting that for the lack of information on cost, we have used the data in [7][107]. It is also important to understand that a preheating method may not achieve the maximum or minimum value simultaneously for any two indicators. The results of this analysis are shown in Fig. 16.

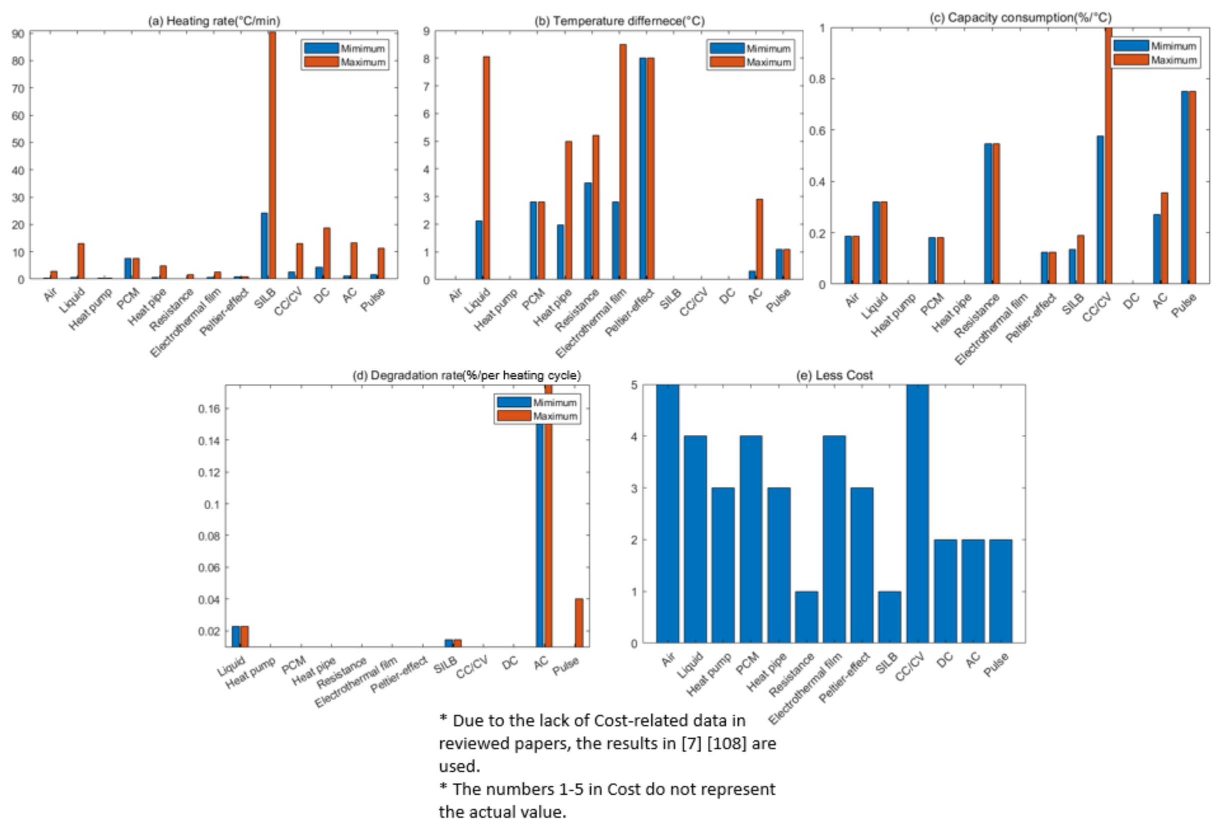


Figure 16 Comparisons of preheating methods under 5 metrics using maximum and minimum value by bar chart

6.2 Comparison methodology for radar map

Based on the results shown in the bar chart, we have also created a radar chart to provide a more intuitive comparison of the performance of each preheating method. However, instead of using actual data from the papers we collected, we have developed a rating scale based on the results obtained from the bar chart. This rating scale qualitatively displays the score of each warm-up method under each indicator, in the form of a radar map. The methodology for creating the radar map is as follows:

1. Define indicators demonstrating positive results: Keep the ‘heating rate’ and ‘less cost’ and change the other three to: 'Temperature uniformity', 'Less Capacity Consumption' and 'Battery health'.
2. In accordance with the collected data in the bar chart, which provides a visual depiction of the relative performance of each preheating method under each indicator, we have evaluated and ranked each preheating method according to specific indicators. Subsequently, we have assigned corresponding score values to reflect their performance.
3. The scoring system ranges from 1 to 5, with higher scores indicating superior performance within a given indicator. For instance, a score of 5 in the "Heating Rate" indicator signifies the highest heating rate. Notably, a score of 5 in the "Temperature uniformity" indicator denotes optimal temperature uniformity, indicating the method's ability to maintain a consistent temperature across the battery.

It is important to emphasize that these rankings and scores presented in our report are based on the analysis of specific data pertaining to each preheating method from the papers we collected. The outcomes and rankings are derived from this data and should be interpreted within that context. The results are shown in Fig. 17, which visually represents the rankings and scores for easy reference and interpretation.

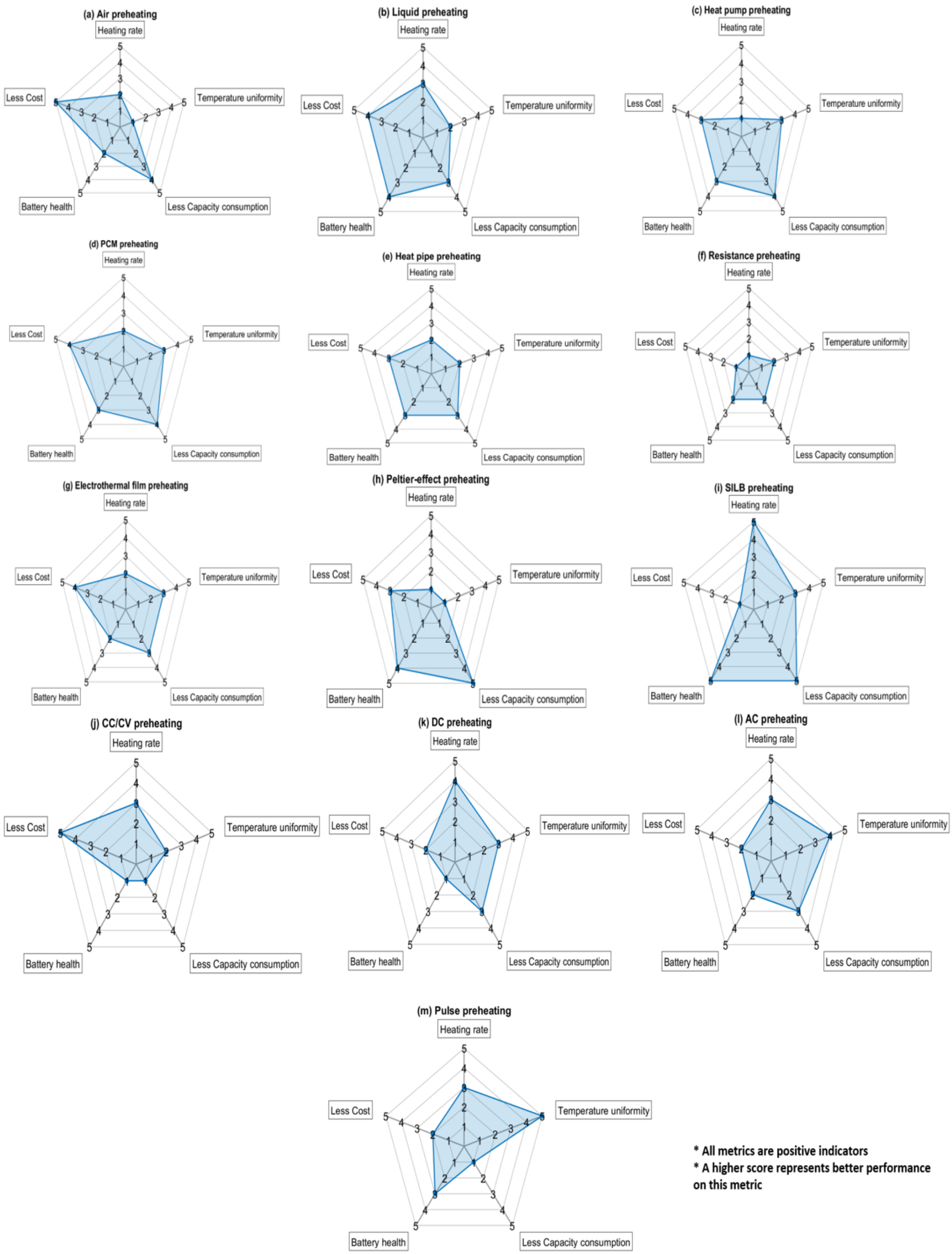


Figure 17 Comparisons of 5 metrics of preheating methods by radar map

6.3 Conclusion

Based on the results obtained from the radar map analysis, certain conclusions can be made for different preheating methods. For the external preheating methods, both liquid preheating and heat pipe preheating demonstrate satisfactory heating rates. On the other hand, PCM preheating shows the potential to ensure temperature uniformity, which helps to mitigate temperature gradients and promote optimal battery performance. In the case of internal preheating methods, these preheating methods can achieve more uniform temperature distribution by harnessing internal heat. The self-heating lithium battery has the highest heating rate but also comes with a high cost. Besides, a long way exists for this method to be used in EVs. Pulse preheating and AC preheating methods show good performance in terms of temperature uniformity, which positively impacts battery health. These methods also show satisfactory heating rates.

In summary, each preheating approach presents unique advantages within the context of the five evaluation indicators. Future research should focus on identifying the optimal approach based on these indicators to enhance the implementation of preheating methods. This can be achieved by optimizing heat transfer paths, refining design parameters, and enhancing heat transfer coefficients. Furthermore, developing control-oriented models with improved computational capacity and accuracy is crucial. These models should accurately capture battery health, thermal behavior, and other pertinent factors. By incorporating such models, the preheating process can be executed with maximum performance and efficiency.

Despite the progress made thus far, it is clear that further improvements are necessary to facilitate a more efficient warm-up process and enhance the performance of electric vehicles in cold weather conditions. Continued research and advancements in this domain are imperative to optimize preheating methods and improve electric vehicle performance during winter operations.

7 Future work: Methodology for Assessing Lifetime GHG Impact of Thermal Preconditioning

Use a battery electrothermal model with degradation mechanisms to calculate the impact of preconditioning or lack of preconditioning in battery degradation.

Objectives:

- Choose realistic efficiency of preconditioning methods following the literature review
- Investigate a range of preconditioning settings while plugged-in for
- Battery cooling in hot climate that will maintain SEI growth within state of health specs.
- Battery heating in cold environments for maintaining range and avoiding Li-plating for specific charging specs
- The reduction of battery life w/o preconditioning will then be compared and contrasted with the energy used for the pre-conditioning to establish a basis for lifetime efficiency.
- The local grid CO_2 content and its projections will be considered for a geographically diverse GHG impact of thermal preconditioning.

Goals/ Deliverables:

- A coupled electrical-thermal battery degradation model and a preconditioning approach for battery life
- A quantification of the trade-off between energy consumption from preconditioning method (heating and cooling) and battery life
- An analysis and a model on GHG emissions from preconditioning

Reference

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Appendix

Table A.1 Summary of heating rate and differences in battery in reviewed air preheating method

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
Air preheating	[1] Experimental study on the effects of pre-heating a battery in a low-temperature environment. In 2012 IEEE Vehicle Power and Propulsion Conference https://doi.org/10.1109/VPPC.2012.6422509												
	Tested in 4 cases to compare performance after preheating	Battery system model; air heater model; powertrain model	-20 to 25	-	20	-	-	Battery	0.9 °C/min	-	-	Greater mileage	-
	[2] Heating strategies for Li-ion batteries operated from subzero temperatures. Electrochimica Acta, 2013 https://doi.org/10.1016/j.electacta.2013.03.147												
	-	Electrochemical–thermal (ECT) coupled model	-20 to 20	NMC	2.2	Cyl.	44	Battery	40 °C/ 85s (R_{heater}=0.4 Ω)	-	5%-10% of capacity (discharge voltage level from2.66V to 3.40 V)	-	-
	[3] Preheating Simulation of Power Battery. Proc Int. Conf Human-centric Comp & Embedded and Multimedia Comp, 2011 https://doi.org/10.1007/978-94-007-2105-0_55												

	-	Mathematical Model of Battery and Aluminum Shell in Fluent software	-20 to 15	LFP	10	Prism.	1500	-	35 °C/ 15 min (Inlet temp =50°C, velocity=4 m/s)	-	-	-	Higher velocity of air →bigger temp gradients, harmful to battery life
	[4] Design of electric air-heated box for batteries in electric vehicles. Chin. J. Power Sources, 2013. (in Chinese)												
	Heating the battery with the designed air heating box	-	-15 to 0	-	-	-	-	40V DC	0.69 °C/min	-	-	-	-
	[5] Performance of plug-in hybrid electric vehicle under low temperature condition and economy analysis of battery pre-heating. Journal of Power Sources, 2018 https://doi.org/10.1016/j.jpowsour.2018.08.093												
	-	PHEV powertrain model with convective heating function	-20 to 13	LFP	60	-	2000	EGU (Engine and generator unit) or grid	33 °C/ 714 s	-	-	-	With preheating, battery degradation reduced from 1.647×10^{-4} to 0.336×10^{-4} (capacity is normalized to 1)
	[6] Design of the control scheme of power battery low temperature charging heating based on the real vehicle applications. In 2013 IEEE vehicle power and propulsion conference (VPPC) https://doi.org/10.1109/VPPC.2013.6671673												
	Comment: not well written; an external charger was used to power a PTC and blow heated air for battery warm-up												
	Environmental chamber and real vehicle test in winter were performed based on a Changan electric vehicle	-	-5 to 5	-	90	-	-	External Source	10 °C/ 24 min	-	-	-	-

Table A.2 Summary of heating rate and differences in battery in reviewed liquid preheating method

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
	[10] Evaluating the performance of liquid immersing preheating system for Lithium-ion battery pack. Applied Thermal Engineering, 2021												

Liquid preheating	https://doi.org/10.1016/j.applthermaleng.2021.116811												
	Comment: heat transfer of fluid and the number of batteries affect the rising temp rate												
	A prototype experiment was set up to validate the CFD model	3D CFD in COMSOL	-28 to 25	-	50	Prism.	-	-	4.18° C/min	Under 4 °C among cells in the pack	-	-	-
	[11] Numerical analysis of temperature uniformity of a liquid cooling battery module composed of heat-conducting blocks with gradient contact surface angles. Applied Thermal Engineering, 2020 https://doi.org/10.1016/j.applthermaleng.2020.115509												
	Comment: The optimal inlet velocity of the fluid medium is 0.015m/s												
	An experiment was conducted to validate the model	3D CFD in ANSY Fluent	-	-	2.2	Cyl.	-	-	-	8.05 °C among cells in the pack (24 cells in each row)	-	-	-
	[12] Multi-objective optimization design for a double-direction liquid heating system-based Cell-to-Chassis battery module. International Journal of Heat and Mass Transfer, 2022 https://doi.org/10.1016/j.ijheatmasstransfer.2021.122184												
	-	CFD in Fluent	-40 to 40	LFP	5	Prism.	165	-	6.7 ° C/min (double direction liquid)	8.8 ° C among cells in the pack	-	-	-
	[13] Integrated All-Climate Heating/Cooling System Design and Preheating Strategy for Lithium-Ion Battery Pack. Batteries, 2022 https://doi.org/10.3390/batteries8100179												
	Comment: Three sides and an extra cooling plate were added in the middle of the battery pack												
	A battery charging experiment was conducted to verify the accuracy of the model	Battery heat generation and transfer model and cooling structure model in COMSOL	-20 to 15	LFP	30	-	795	-	35 ° C/ 1740 s	Below 5°C of battery pack (flow rate greater than 0.8m/s)	-	-	-
	[14] An optimized energy management strategy for preheating vehicle-mounted li-ion batteries at subzero temperatures. Energies, 2017 https://doi.org/10.3390/en10020243												
	Real vehicle testing w/ and w/o	Electro-thermal model and	-10 to 2	LFP	180	-	5800	External source	12 ° C/ about 1157 s	3.1 ° C among differ	14.38 KWh	-	The battery fade ratio of preheating and

	preheating (to 2 °C)	degradation model								ent cells			unpreheating is 0.015% and 0.023% in the experiment respectively.
	[15] Improvement of thermal characteristics and discharge parameters of NCM811 power battery preheated by oil immersion. Chemical progress, 2022(in Chinese)												
	Comment: immersion preheating												
	Experiment based on oil immersion preheating	-	-20 to 10	NCM	4.6	-	70	External source	13.04 °C/min	3.5°C of different points on the surface of a battery	-	Internal and polarization resistances decreased to 37.9% and 21.1% of unpreheating (SOC:33.3%)	-
	[16] Thermal insulation and preheating Performance of Lithium Battery based on PCM. Chemical Engineering, 2022 (in Chinese)												
	Comment: coolant + PCM (for warming)												
	The temperature rising curve in the experiment consistent with that in model	Battery preheating model and insolation model	-	LFP	20	Prism.	-	External source	7.26°C/min	4.24°C among cells	-	-	-
	[17] Investigation into heating system of lithium-ion battery pack in a low-temperature environment. J. South China Univ. Technol.(Nat. Sci.), 2016 (in Chinese)												
	Comment: immersion preheating												
	Pack 16S cells. Immersed in transformer (insulating) oil External Heater by a high voltage (220 V) power supply.	Thermal sim model of battery unit and the pack heating device in ANSYS software.	-30 to 0 -20 to 0 -10 to 0	-	37	Prism.	-	External source	30 °C/ 35 min 20 °C/ 22 min 10 °C/ 12 min	3°C among cells in the 16 cell series pack	-	-	-
	[18] Modeling and Thermal Analysis of Low-temperature hybrid preheating system for Cluster Screening of Lithium ion Battery Packs. Journal of Tongji University (Natural Science), 2021 (in Chinese)												
	Comment: cooling plate and PTC												
	-	Sim in FLUENT for the fluid-solid coupling heat transfer	-40 to 0	LFP	5	-	165	-	3.56 °C/min	~20.9 °C among cells	69500.7 J	-	-

	[19] Design research on battery heating and preservation system based on liquid cooling mode. Journal of Hunan University, 2017 (in Chinese)												
	The liquid-cooled power battery system installed on the vehicle and powered on at high voltage.	The transient heat conduction equation and the finite element method used for model	-28 to 10	-	-	-	-	-	38 °C/ 70min	1 °C among cells	-	-	-
	[20] Analysis of Heat Dissipation and Preheating Module for Vehicle Lithium Iron Phosphate Battery. Energies, 2021 https://doi.org/10.3390/en14196196												
	-	The heat generation model and Liquid cooling model in Solidworks	-20 to 25	LFP	-	Prism.	-	-	45 °C/ 1500 s ($T_{coolant}$ 35°C)	8.332 °C among cells	-	-	-
	[21] Effect analysis on performance improvement of battery thermal management in cold weather. Journal of Energy Storage, 2022 https://doi.org/10.1016/j.est.2021.103728												
	-	CFD model of 6 batteries and a heating plate	-20 to -	-	150	-	-	-	4 °C/ min (0.525kg/s and 60 °C)	2.11 °C among cells	-	-	-
	[22] Thermal analysis and optimization of an EV battery pack for real applications. International Journal of Heat and Mass Transfer, 2020 https://doi.org/10.1016/j.ijheatmasstransfer.2020.120384												
	Comment: best performance at minimum energy consumption found; considering reversible heat is better on mating test results												
	EV-ARC test and heating test	Heat generation and transfer model and 3D simulation of the battery pack with cooling plate	-20 to 5	-	153	-	-	-	0.5 °C/min (8 L/min, 40°C)	6 °C among cells	-	-	-

Table A.3 Summary of heating rate and differences in battery in reviewed heat pump preheating method

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact		
												Performance	Durability	Environment

Heat pump preheating	[27] Battery thermal management strategy utilizing a secondary heat pump in electric vehicle under cold-start conditions. Energy, 2023 https://doi.org/10.1016/j.energy.2023.126827													
	-	Thermal model and transient heat pump model	-5 to 15	-	1	-	-	-	20 °C/ 60 min	-	-	-	-	-
	[28] Evaluation of the energy consumption of a thermal management system of a plug-in hybrid electric vehicle using the example of the Audi Q7 e-tron. SAE International Journal of Passenger Cars-Mechanical Systems, 2018 http://dx.doi.org/10.4271/06-11-03-0017													
	Real vehicle test	-	-	-	-	-	-	-	-	-	-	Realizing an increase of driving range of > 10% with heat pump	-	The CO2 is 6 g/km with heat pump for cabin heating

Table A.4 Summary of heating rate and differences in battery in reviewed PCM preheating method

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
PCM preheating	[35] A fast-heat battery system using the heat released from detonated supercooled phase change materials. Energy, 2021 https://doi.org/10.1016/j.energy.2020.119496												
	A device designed to trigger the solidification of the subcooled PCM to release heat to battery	-	5 to 20	-	3.2	Cyl.	-	-	15°C / 2 min (PCM with subcooling) 15°C / 37 min (PCM without subcooling)	-	-	Increase in discharge capacity and power up to 9.87% and 7.56% in the PCM with subcooling	- -
	[36] Experimental investigation of thermal management system for lithium ion batteries module with coupling effect by heat sheets and phase change materials. International Journal of Energy Research, 2018 https://doi.org/10.1002/er.4081												
	Designation of battery module with composite PCMs and experiment for thermal properties	-	-15 to -	-	-	Cyl.	-	External power source	0.5 - 1°C /min with heat sheets from 40 to 65 °C	2.82 °C among cells in the battery module	2000 - 2500 J/°C	-	- -

Table A.5 Summary of heating rate and differences in battery in reviewed heat pipe preheating method

Method	Experiment	Model	Ambient -	Cell	Cell Cap	Cell	Cell Mas	Power	Heating Rate	Temp. Diff. ΔT	Energy/	Impact

			final Tem p. (°C)	Ch em .	. (Ah)	Ge om .	s (g)	Sour ce			Cap acit y Con sum ptio n	Performance	Dur abili ty
Heat pipe preheating	[39] Experimental investigation on EV battery cooling and heating by heat pipes. Applied Thermal Engineering, 2015 https://doi.org/10.1016/j.applthermaleng.2014.09.083												
	L-shape heat pipe inserted in the cell gap	-	-15 to 0 -20 to 0	-	-	-	-	External source (DC)	15°C / 1200s or 300s (20 or 40 °C hot fluid) 20°C / 1500s or 500s (20 or 40 °C hot fluid)	-	-	-	-
	[40] Experimental investigation on an integrated thermal management system with heat pipe heat exchanger for electric vehicle. Energy conversion and management, 2016 https://doi.org/10.1016/j.enconman.2016.03.066												
	Test with heat pipe heat exchanger and heat pump air conditioning to research the performance of this integrated system under different working conditions	-	-20 to 0	-	-	-	16030	-	20 °C / 13.33 min	-	1.11 W/ °C	-	-
	[41] Experimental investigation of preheating performance of lithium-ion battery modules in electric vehicles enhanced by bending flat micro heat pipe array. Applied Energy, 2023 https://doi.org/10.1016/j.apenergy.2023.120896												
	Designation of battery module with bending FMHPAs and experiment of this	-	-20 to 0	LFP	52	Prism.	-	External source	1 °C / min	Below 5 °C at single cell and pack level	-	-	-
	[42] Experimental study on heating performance of pure electric vehicle power battery under low temperature environment. International Journal of Heat and Mass Transfer, 2021 https://doi.org/10.1016/j.ijheatmasstransfer.2021.121191												
	Designation of battery module with TiO_2 CLPHP and experiment of this	-	-20 to 0	LFP	68	Prism.	-	-	1.62 °C / min	-	-	Discharge voltage increased to 3.06V(-10 °C), 3.01V(-20 °C) and 2.99V(-30 °C), while the discharge	-

												capacity increased by 3.9%,11.6% and 24.4% respectively	
	[43] Investigation of thermal management of lithium-ion battery based on micro heat pipe array. Journal of Energy Storage, 2021 https://doi.org/10.1016/j.est.2021.102624												
	Comment: integration of cooling and heating; negative impact on each other												
	Li-ion battery heating unit based on MHPA for experiment	3D heat transfer model and model of the Li-ion battery heating unit based on MHPA in COMSOL Multiphysics	-30 to 0	LFP	18	Prism.	-	Experiment: external source Model: -	Model: 30°C / 20 min (heating power 30 W)	Below 3.03 °C among cells in the pack	-	-	-
	[44] Inclined U-shaped flat microheat pipe array configuration for cooling and heating lithium-ion battery modules in electric vehicles. Energy, 2021 https://doi.org/10.1016/j.energy.2021.121433												
	3p4s battery pack with 6 U-shaped FMHPAs for experiment	-	-10 to 0 -10 to 10	NMC	50	Prism.	-	External source: PTC	0.56°C / min 0.61°C / min	Below 5°C at the surface of battery	-	-	-
	[45] Experimental investigation on cooling/heating characteristics of ultra-thin micro heat pipe for electric vehicle battery thermal management. Chinese Journal of Mechanical Engineering, 2018 (in Chinese)												
	5p battery pack with 12 UMHPs (4 in group) for experiment	-	-20 to 20	-	50	-	-	-	40°C / 455s-502s (heating power 180W)	~3.4 °C among cells	-	-	-
	[46] Experimental study on preheating thermal management system for lithium-ion battery based on U-shaped micro heat pipe array. Energy, 2022 https://doi.org/10.1016/j.energy.2022.124178												
	Experiment for LIB preheating based U-shape MHPA and PI electric heating film on the upper surface of each layer of batteries	-	-20 to 0	LFP	120	Prism.	-	External source	15 °C / 26 min (Electrical heating power is 32W with heat pipe	Battery level: 1.06 °C (with heat pipe) 0.97 °C (no heat pipe) Module level: 2.35 °C (with heat pipe) 1.97 °C (no heat pipe) Module	-	-	-

Table A.6 Summary of heating rate and differences in battery in reviewed resistance preheating method

		Model										Impact

Method	Experiment		Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Performance	Durability
Resistance preheating	[48] PTC self-heating experiments and thermal modeling of lithium-ion battery pack in electric vehicles. Energies, 2017 https://doi.org/10.3390/en10040572												
	Battery pack with PTC resistance inserted for experiment in two cases: 220V AC as supplying power and battery as supplying power	Heat generation and transfer model and temp rising model (internal and external heat)	-23.3 to -0.5	LMO	35	Prism.	1080	External source: 220V AC and Battery	0.504 °C / min	4.67 °C (-40 to -20) 3.506 °C (-20 to 0) among cells in the pack	~ 13% of the total pack energy	After preheated to 0.5 °C, battery pack can discharge for 10s at 3C pulse current, but not at the 3.5C	-
	[49] Heating character of a LiMn2O4 battery pack at low temperature based on PTC and metallic resistance material. Energy Procedia, 2017 https://doi.org/10.1016/j.egypro.2017.03.602												
	Comment: higher battery temperature and better pack thermos-consistency of MRF side heating with same energy consumption												
	PTC bottom heating and Metallic resistance film side heating	-	-12 to 2	LMO	35	Prism.	-	Grid power	Average rising rate of external and internal battery cells are 4.34 and 2.77 °C / h Respectively (PTC) ~0.34 °C/min (MRF)	5.2 °C among cells (PTC) 2.81 °C among cells (MRF)	-	-	-
	[50] Researches on heating low-temperature lithium-ion power battery in electric vehicles. In 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), 2014 https://doi.org/10.1109/ITEC-AP.2014.6941276												
	Experiments based on the heating aluminum plate twined by PTC resistance wire heating method	Battery heat generation model; geometric model; finite element model	-40 to 2.5	LMO	35	-	-	External source: 220V AC	42.5 °C / 25 min	-	-	Discharge capacity increases from 21.9Ah to 24.11 Ah at 0.3C after heated	-

Table A.7 Summary of heating rate and differences in battery in reviewed electrothermal film preheating method

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
	[52] Preheating performance by heating film for the safe application of cylindrical lithium-ion battery at low temperature. Fire Technology, 2022 https://doi.org/10.1007/s10694-022-01251-0												
	Comment: symmetric PI film better than spiral case in the uniformity of temperature distribution; Higher power of heating film can cause increased power consumption and worse temp difference												
Electrothermal film preheating	Experiment based on the PI heating film attached on both sides of the battery	Battery electro-thermal model and battery simulation model in Fluent	-10 to 25	LMO	-	Cyl.	-	Battery	35 °C / 395 s(1W) 35 °C / 190 s(3W) 35 °C / 126 s(5W)	8.5 °C in the battery level (5W)	540 J (heating power is 3W)	Ohm resistance from 0.12 (-15 °C) to 0.05 (25 °C) at SOC=0.5	-
	[53] Low current rate discharge with external heating at low temperature. In 2015 IEEE Vehicle Power and Propulsion Conference (VPPC) https://doi.org/10.1109/VPPC.2015.7352973												
	Electrothermal film powered by 110V DC at the bottom of battery for experiment	Thermal model	-27 to 5 -17 to 0	LFP	80	-	-	110V DC power supply	32 °C / 50 min 17 °C / 40 min	-	1.713 kWh 0.9515 kWh	The discharge energy has been promoted by 0.36031(-17 °C) and 0.7664 (-27 °C) after heating respectively	-
	[54] Low-temperature Heating Experiment of Power Battery Module for Electric Vehicle. Batteries, 2021 (in Chinese)												
	The heating film under the battery pack for the experiment	Thermal model and battery simulation model in STAR-CCM	-	LMO	52	-	-	External source	About 0.6 °C / min (heating power 100W)	-	-	-	-
	[55]Preheating method of lithium-ion batteries in an electric vehicle. Journal of Modern Power Systems and Clean Energy, 2015 https://doi.org/10.1007/s40565-015-0115-1												
	Experiment based on wide-line metal film installed in four heaters between 3 cells	-	-40 to -	LMO	35	-	-	Battery	2.67 °C / min	-	-	The voltage and power performance of the battery pack were improved (1C), and the discharging and charging capacity restored almost to total	-

												and half its room-temperature level	

Table A.8 Summary of heating rate and differences in battery in reviewed Peltier effect preheating method

Method	Experiment	Model	Ambient-final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
Peltier effect preheating	[57] A novel thermal management for electric and hybrid vehicles. IEEE transactions on vehicular technology, 2005 https://doi.org/10.1109/TVT.2004.842444												
	Comment: cooling is more effective and efficient than heating												
	Experiment based on Peltier-effect thermoelectric heat pumps	Thermal management model in SPICE	17 to 37 (frontal battery box) 17 to 29 (rear battery compartment)	-	60	-	-	Battery	20 °C / 20 min 12 °C / 20 min	8 °C (Heat lost to ambient at the hose systems)	2.5% of capacity	-	-

Table A.9 Summary of heating rate and differences in battery in reviewed self-Heating Lithium-Ion Battery

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
Self-heating lithium-ion battery	[58] Rapid self-heating and internal temperature sensing of lithium-ion batteries at low temperatures. Electrochimica Acta, 2016 https://doi.org/10.1016/j.electacta.2016.09.117												
	Nickel foil sheets in parallel inserted within the 2-sheet cell.	-	-20 to 0 -30 to 0 -40 to 0	LMO	10	-	210	Battery	20 °C/ 12.5 s 30 °C/ 19.2 s 40 °C/ 29.4 s	Foil temperature increases much faster than the battery surface temperature	2.9% 4.1% 5.4% Of capacity	The self-heated cell yields a discharge/ regeneration power of 1061/1425 w/kg at 50% SOC in the ambient temp of -30 °C	After 500 preheating at CCCV (1C), the cell capacity fade is less than 7.2% -
	[59] Lithium-ion battery structure that self-heats at low temperatures. Nature, 2016 https://doi.org/10.1038/nature16502												
	One nickel foil sheet inserted in cell for tests.	-	-20 to 0 -30 to 0 -40 to 0	LMO	7.5	-	160	Battery	20 °C/ 19.5 s 30 °C/ 29.6 s 40 °C/ 42.5 s	-	3.8% 5.5% Of capacity	14 min charged to 80% at the degree of -30	SHLB can achieve 500 cycles in 3C fast charging at -30 °C, while the conventional cells would lose

													20% capacity after 12 cycles -
	[60] A fast rechargeable lithium-ion battery at subfreezing temperatures. Journal of The Electrochemical Society, 2016 https://iopscience.iop.org/article/10.1149/2.0681609jes/meta												
	One nickel foil sheet inserted in cell for tests.	Electrochemical-thermal coupled model in software AutoLion 1D	-10 to 10 -20 to 10 -30 to 10	LMO	10	-	206	External source (pulse)	20 °C/ 54 s 30 °C/ 77 s 40 °C/ 90 s	-	-		
	[61] Rapid restoration of electric vehicle battery performance while driving at cold temperatures. Journal of Power Sources, 2017 https://doi.org/10.1016/j.jpowsour.2017.10.029												
	Comment: control strategy named 'Battery Heating While Driving' proposed, where braking energy used for internal heating												
	Battery with two inserted nickel foils tested according to EV load profile	-	-10 to 10 -20 to 10 -30 to 10 -40 to 10	LMO	9.5	-	210	-	20 °C/ 33 s 30 °C/ 46 s 40 °C/ 56 s 50 °C/ 112 s	-	-		
	[62] Computational design and refinement of self-heating lithium ion batteries. Journal of Power Sources, 2016 https://doi.org/10.1016/j.jpowsour.2016.08.028												
	Experiments carried out to obtain data for validation of the present ECT model.	Electrochemical-thermal coupled model.	-20 to 0	LMO	10	-	-	-	20 °C/ 27.7 s (one sheet) 20 °C/ 20.8 s (two sheets) 20 °C/ 19.4 s (three sheets)	Lower than 5°C (3 sheets) between surface of battery and Ni foil	4.15% 3.23% 3.03% Of capacity		
	[63] Innovative heating of large-size automotive Li-ion cells. Journal of power sources, 2017 https://doi.org/10.1016/j.jpowsour.2016.12.102												
	Comment: More Ni sheets inserted better for temperature gradient across cell thickness												
	-	Electrochemical-thermal coupled model.	-30 to 0	-	40	-	-	-	-	-	-		
	[64] Improving temperature uniformity of a lithium-ion battery by intermittent heating method in cold climate. International Journal of Heat and Mass Transfer, 2018 https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.159												
	Comment: heating for some time and stopping heating to ensure uniformity												
	-	A three-dimension heating finite element model is	-	LMO	-	Prism.	-	-	-	3-4 kelvin across the thickness of battery (heating	-		

		established.								for 0.1 s and stopping for 0.3s)			

Table A.10 Summary of heating rate and differences in battery in reviewed CC/CV discharging

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
CC/CV discharge	[2] Heating strategies for Li-ion batteries operated from subzero temperatures. Electrochimica Acta, 2013 https://doi.org/10.1016/j.electacta.2013.03.147												
	Comment: CC discharge												
	-	Electrochemical–thermal (ECT) coupled model	-20 to 15	NCM	2.2	Cyl.	-	Battery	35 °C/ 420 s (2C)	-	-	-	-
	[65] Analysis of low temperature preheating effect based on battery temperature-rise model. Energies, 2017 https://doi.org/10.3390/en10081121												
	Comment: CC discharge												
	Discharge process test for self-heating at low temperature	Temperature-rise model with the dynamic characteristic of the battery temperature and SOC.	-10 to 5	$Li_xNiCoAIO_2$	2.6	Cyl.	45	Battery	15 °C/ 280 s (2C) 15 °C/ more than 1080 s (1C)	-	Not exceed 15% 30% of the rated capacity	-	-
	[2] Heating strategies for Li-ion batteries operated from subzero temperatures. Electrochimica Acta, 2013 https://doi.org/10.1016/j.electacta.2013.03.147												
	Comment: CV discharge												
	-	Electrochemical–thermal (ECT) coupled model.	-20 to 20	NCM	2.2	Cyl.	-	Battery	40 °C/ 360 s (2.8V) 35 °C/ 197 s (2.5V)	-	23% of capacity	-	-
	[66] Multistage CC-CV charge method for Li-ion battery. Mathematical Problems in Engineering, 2015 https://doi.org/10.1155/2015/294793												
	Comment: multistage CC-CV charge												
	CC-CV, two-stage CC-CV, and multistage CC-CV tested in battery.	Electrochemical and first-order RC equivalent circuit model.	-10 to -	LFP	1.37	Cyl.	-	Battery	-	-	Multistage CC-CV decreases power consumption by 3.04% compared with CC discharging	-	Multistage CC-CV decreases the capacity fade by 5.65% compared with CC

													discharging
	[67] Multi-objective optimization discharge method for heating lithium-ion battery at low temperatures. IEEE Access, 2018 https://doi.org/10.1109/ACCESS.2018.2837652												
	Comment: multi-objective optimization discharge												
	The parameters identified by test data	Thevenin equivalent circuit model and the temperature-rise model	-10 to 5	LFP	5	-	145 g	Battery	15 °C/ 291.33 s	-	-	-	-
	[68]Comparing optimal battery warm-up strategies based on self-heating. In 2017 IEEE 56th Annual Conference on Decision and Control (CDC) https://doi.org/10.1109/CDC.2017.8264231												
	Comment: CV-CC-rest phase discharge; energy and warm-up time as objectives; power deliverability as a terminal constraint												
	-	Coupled electrothermal model	-20 to 0 -20 to 10	LFP	2.3	Cyl.	-	battery	20 °C/ 93.06s (Power as a terminal point) 30 °C/ 78.03s (Temp as a terminal point)	-	ΔZ is 0.1199. ΔZ is 0.1552.	-	-

Table A.11 Summary of heating rate and differences in battery in reviewed DC preheating method

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
DC preheating	[69] An optimal internal-heating strategy for lithium-ion batteries at low temperature considering both heating time and lifetime reduction. Applied Energy, 2019 https://doi.org/10.1016/j.apenergy.2019.113797												
	Testing system and monitoring system in the experimental platform.	Battery heat generation model, the lumped thermal equivalent circuit model, and the semi-empirical fade model.	-30 to 2.1	$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$	8	-	300	-	32.1 °C/ 103 s	-	-	The heated battery can offer 8.7/32.7 times the discharge/charge power and 62.46 times the discharge energy of the unheated battery	The capacity loss is only 1.4% after 500 repeatedly heating -
	[70] Experimental study on pulse self–heating of lithium–ion battery at low temperature. International Journal of Heat and Mass Transfer, 2019 https://doi.org/10.1016/j.ijheatmasstransfer.2019.02.020												
	Comment: heating efficiency is 15.3%; The lower discharge voltage and higher polarization in DC heating easily cause cracks in the electrode material, while the longer battery life in pulse heating is attributed to the higher discharge voltage												
	Three current values (maximum current (11	N/A	-10 to 10	LCO	2	Cyl.	45	-	20 °C/ 280 s (DC-8A)	-	-	-	The SOH drops to 0.8 at the 81st cycle.

	A), minimum current (8 A) and mean current (9.5 A)) performed the continuous DC heating.												-

Table A.12 Summary of heating rate and differences in battery in reviewed AC preheating method

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
AC preheating	[71] Cooling and preheating of batteries in hybrid electric vehicles. In 6th ASME-JSME Thermal Engineering Joint Conference, 2003 https://www.researchgate.net/profile/Andreas-Vlahinos/publication/228780594_Cooling_and_preheating_of_batteries_in_hybrid_electric_vehicles/links/0c96053189038d5e39000000/Cooling-and-preheating-of-batteries-in-hybrid-electric-vehicles.pdf												
	-	A simple lumped capacitance calculation and finite element analysis in software ANSYS.	-40 to 6	Ni MH	13	-	4900	-	46 °C/ 6 min (AC-110 Arms 60 Hz)	-	-	AC can decrease the resistance from 1.36 Ohm in -30°C to 0.205 Ohm in 25°C, which makes the battery deliver more power	-
	[72] HEV battery heating using AC currents. Journal of Power Sources, 2004 https://doi.org/10.1016/j.jpowsour.2003.10.014												
	AC provided by 60 Hz source.	-	-20 to 20	Ni MH	6.5 (16 series)	-	-	-	40°C/ 3 min (AC-80Arms 10-20 kHz)	-	-	At both -20 °C and -30 °C, 10-20 kHz AC currents at 60-80 Arms can restore the battery resistance to values close to that at 25 °C	- -
	[73] Temperature-adaptive alternating current preheating of lithium-ion batteries with lithium deposition prevention. Journal of The Electrochemical Society, 2015 https://iopscience.iop.org/article/10.1149/2.0961602jes/meta												
	Comment: the maximum permissible amplitudes of the heating current without lithium deposition at different frequencies determined at each temperature in the multistep AC preheating method												
	Sinusoidal alternating	The equivalent	-25 to 5	70 %	1	-	25.6	-	30°C/ 800 s	-	-	-	-

	current was used for the test.	electric circuit (EEC) models fitted through the EIS data and the maximum permissible AC and the heat generation rate combined in the model.		NCM and 30 % LMO					(AC-100 Hz -20 to -5: 3.5 A -15 to -10: 4 A -10 to -5: 5 A -5 to 0: 6 A 0 to 5: 7 A)				-
	[74] Internal heating of lithium-ion batteries using alternating current based on the heat generation model in the frequency domain. Journal of Power Sources, 2015 https://doi.org/10.1016/j.jpowsour.2014.09.181												
	Experiments to prove model	Equivalent circuit model and the model for the heat generation and the temperature rise in the frequency domain	-20 to 5	$Li_xNi_{0.8}Co_{0.15}Al_{0.05}O_2$	2.8	Cyl.	46	-	30°C/ 1000 s (AC-7A 1 Hz)	Less than 2 °C in battery level	-	-	Capacity loss is not seen after repeated preheating experiments -
	[75] A rapid low-temperature internal heating strategy with optimal frequency based on constant polarization voltage for lithium-ion batteries. Applied Energy, 2016 https://doi.org/10.1016/j.apenergy.2016.05.151												
	battery heated by increasing SAC with various sets of frequencies	Electro-thermal coupled model	-15.4 to 5.6	NCM	-	-	-	-	21°C/ 338 s (AC-1377 Hz)	Less than 1.6 °C in battery level	-	-	After heating 30 times, IC peaks are almost the same, which means there is no obvious detrimental effect on the SOH of LIBs -
	[76] An alternating current heating method for lithium-ion batteries from subzero temperatures. International Journal of Energy Research, 2016 https://doi.org/10.1002/er.3576												
	Comment: comparison of AC and pulse heating methods; when the frequency exceeds 10 Hz, the capacity and impedance would barely experience any attenuation												
	Experiments with different current amplitudes, frequencies, and waveforms	A thermal model considering battery safe operating voltage limits with heat generation rate and temperature	-24 to 7.79 -24 to 25.6	$LiMnNiCoO_2$	2.3	Cyl.	45	-	31.79°C/ 600 s (SAC-30Hz 10A) 49.6°C/ 600 s (Rectangular pulse AC 30Hz 10A	-	-		After 20 and 40 times heating (rectangular pulse-1Hz-10A), 3.7% and 6.6% capacity fading are observed, and DC resistance increases by

													1.2% and 2.2% respectively.
	[77] Experimental investigations of an AC pulse heating method for vehicular high power lithium-ion batteries at subzero temperatures. Journal of Power Sources, 2017 https://doi.org/10.1016/j.jpowsour.2017.09.063												
	AC pulse heating tests with different parameters, the AC pulse heating cycle tests, the low temperature charge tests, and the calibration tests.	-	-25 to 5	LFP	30	-	675	-	30°C/ 1800 s (SAC-1Hz 60A)	Temperature inconsistency between the cell interior and surface is less than 5°C	-	-	The AC preheating does not cause irreversible damage to the battery even in the low frequency range (0.5 Hz) under normal voltage protection limitations for the battery.
	[78] A novel echelon internal heating strategy of cold batteries for all-climate electric vehicles application. Applied Energy, 2018 https://doi.org/10.1016/j.apenergy.2018.03.052												
	Comment: the echelon heating strategy of variable currents.												
	EIS tests, AC heating tests, Echelon heating tests, life tests and performance tests	The Butler-Volmer equation and a novel electro-thermal coupled model	-20 to 10	$LiMnNiCoO_2$	3	Cyl.	46	-	2.59 °C/ min	2.9 °C among cells in pack	-	-	After heating 40 times, there is no obvious capacity deterioration.
	[79] An automotive onboard AC heater without external power supplies for lithium-ion batteries at low temperatures. IEEE Transactions on Power Electronics, 2017 https://doi.org/10.1109/TPEL.2017.2768661												
	Comment: Only triangle current generated by heater and some heat lost in mosfet												
	An onboard AC heater proposed to heat lithium-ion batteries without the requirement of external power supply	-	-20 to 0 -30 to 0	$LiMnNiCoO_2$	2.5	Cyl.	-	On board AC heater-battery	1.54 °C/ min (AC-7.8A, 833Hz) 2.4 °C/ min (AC-7.8A, 20 kHz) 3.33 °C/ min (AC-10.6A, 500Hz)	Only 0.3 °C between two cells, but the unbalance in SOC or internal resistance will cause	7.1% of cell energy 6.7% of cell energy 7.7% of cell energy	-	-

										a large temp difference between cells.			
	[80] A sine-wave heating circuit for automotive battery self-heating at subzero temperatures. IEEE Transactions on Industrial Informatics, 2019 https://doi.org/10.1109/TII.2019.2923446												
	A high-frequency sinewave (SW) heater based on resonant LC converters to heat the battery	Modeling of the Heating Current and Efficiency and development of heating model	-20 to 0	$LiMnNiCoO_2$	6 series 2.5	Cyl.	46	On board AC heater-battery	1.54 °C/min (AC-6.8A, 40 kHz)	-	5.4% of cell energy	-	-
	[81] Modeling and analysis of high-frequency alternating-current heating for lithium-ion batteries under low-temperature operations. Journal of Power Sources, 2020 https://doi.org/10.1016/j.jpowsour.2019.227435												
	Comment: increasing AC heating frequency can reduce heating time; in the high frequency, the heat generation of the lithium-ion transport cannot be neglected; large current may cause lithium-ion deposition, reducing battery life.												
	A high-frequency AC heater based on buck-boost conversion	High-frequency thermoelectric model based on the heat generation of the ohmic resistance and lithium ion	-20 to 0	$LiMnNiCoO_2$	2.5	Cyl.	46	On board AC heater-battery	2.7 °C/min (AC-4.17A, 45 kHz)	-	6.0% of cell energy	-	The AC frequency should be as high as possible without detrimental effect
	[82] Experimental study on the mechanism of frequency-dependent heat in AC preheating of lithium-ion battery at low temperature. Applied Thermal Engineering, 2022 https://doi.org/10.1016/j.applthermaleng.2022.118860												
	Comment: the increased heat with high AC frequency is not reflected by the simplified Bernardi's heat generation equation												
	EIS tests and heating experiments	-	-20 to 5	-	2.9	Cyl.	47	-	1.42 °C/min (AC-2.48A, 3.9 kHz) 3.26 °C/min (AC-2.48A, 20 kHz)	-	-	-	-
	[83]A fast pre-heating method for lithium-ion batteries by wireless energy transfer at low temperatures. eTransportation, 2023 https://doi.org/10.1016/j.etran.2023.100227												
	Comment: producing SAC based on the onboard wireless charging system												
	Experiment to prove the model	Equivalent circuit model of AC heating system model based on the wireless energy transfer system	-20 to 0	-	2.6	Cyl.	48	-	8.4 °C/min (85 kHz 7800 mA)	2.5 °C among cells across 10s pack	-	-	-

Table A.13 Summary of heating rate and differences in battery in reviewed pulse preheating method

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
Pulse preheating	[84] Capacity degradation minimization oriented optimization for the pulse preheating of lithium-ion batteries under low temperature. Journal of Energy Storage, 2020 https://doi.org/10.1016/j.est.2020.101746												
	Comment: The capacity degradation of the battery is due to the loss of the active material and lithium inventory.												
	Pulse current preheating experiment with a fixed amplitude and a fixed frequency	Electro-thermal model based on electrochemical impedance spectroscopy (EIS) at different temperatures	-20 to 5	$LiNiCoAlO_2$	2.87	-	44.7	-	4.87 °C/ min	-	-	-	The battery only had a capacity loss of 0.035% after 30 heating cycles. -
	[85] The preheating strategy of variable-frequency pulse for lithium battery in cold weather. International Journal of Energy Research, 2020 https://doi.org/10.1002/er.5715												
	Tests to prove the preheating strategy using variable-frequency pulse	Temperature rise model and the thermo-electric coupling model at different temperatures	-20 to 5	-	2.8	Cyl.	44.5	-	25 °C/ 1000s	-	-	-	After 10 preheating cycles, the initial capacity of the cell is changed by only 0.4% -
	[86] Preheating the lithium-ion battery with real-time optimized pulse frequency under low temperatures. Electric Machines and Control, 2021 (in Chinese)												
	Comment: variable frequency pulse												
	Tests for main parameters of battery	A thermoelectric coupling model combining the equivalent circuit and the internal resistance heat generation	-20 to 5	-	5.1	-	83.05	-	25 °C/ 368s	1.1 °C in the battery level	-	-	- -
	[70] Experimental study on pulse self–heating of lithium–ion battery at low temperature. International Journal of Heat and Mass Transfer, 2019 https://doi.org/10.1016/j.ijheatmasstransfer.2019.02.020												

	A circuit module designed to generate a pulse high current in the battery.	N/A	-10 to 10	LCO	2	Cyl.	45	-	20 °C/ 175s (DC-8A)	-	Less than 15% of battery energy	-	
	[87]A rapid lithium-ion battery heating method based on bidirectional pulsed current: Heating effect and impact on battery life. Applied Energy, https://doi.org/10.1016/j.apenergy.2020.115957												
	Low temperature characteristics and the relationship between pulsing parameters and heating rate found by experiments	ECM and thermal model	-10 to 31.3	NCM	50	Prism.	-	-	11.3 °C/min (4C T=0.8s)	-	-	-	
	[88] On the warmup of Li-ion cells from sub-zero temperatures. In 2014 American Control Conference, 2014 https://doi.org/10.1109/ACC.2014.6859350 [89] Energy-conscious warm-up of li-ion cells from subzero temperatures. IEEE Transactions on Industrial Electronics, 2016 https://doi.org/10.1109/TIE.2016.2523440												
	Comment: mutual pulse: pulse between battery and external energy storage system; Power as a terminal constraint; energy efficient												
	Experiments set to validate the models	Equivalent circuit model and thermal model	-20 to 17,5 -20 to 12.25 -20 to 24.3	LFP	-	Cyl.	-	battery	37.5 °C/ 172s (value of penalty on SOC loss is 0) 32.25 °C/ 278s (value of penalty on SOC loss is 0.58) 44.3 °C/ 143s (CV)	-	Comparing the CV with Pulse (penalty value is 0), the total energy loss increases by nearly 35%.	-	

Table A.14 Summary of heating rate and differences in battery in reviewed the combination of internal preheating and external preheating method

Method	Experiment	Model	Ambient - final Temp. (°C)	Cell Chem.	Cell Cap. (Ah)	Cell Geom.	Cell Mass (g)	Power Source	Heating Rate	Temp. Diff. ΔT	Energy/ Capacity Consumption	Impact	
												Performance	Durability
	[47] PTC self-heating experiments and thermal modeling of lithium-ion battery pack in electric vehicles. Energies, 2017												

Discharge heating + PTC	https://doi.org/10.3390/en10040572												
	Comment: promoting restorability of battery discharge capacity with integrating internal and external heat; internal heat good for uniform temp distribution												
	Battery pack with PTC resistance inserted for experiment in two cases: 220V AC as supplying power and battery as supplying power	Heat generation and transfer model and temp rising model (internal and external heat)	-19.3 to -2.4	LMO	35	Prismatic	1080	External source: 220V AC and Battery	0.352 °C / min (SOC =100 %)	4.67 °C (-40 to -20) 3.506 °C (-20 to 0) among cells in the pack	~ 13% of the total pack energy	After preheated to 0.5 °C, battery pack can discharge for 10s at 3C pulse current, but not at the 3.5C	-
Air preheating + Internal preheating (CV-CC-rest phase)	[90]Synthesis of an energy-optimal self-heating strategy for Li-ion batteries. In 2016 IEEE 55th Conference on Decision and Control (CDC) https://doi.org/10.1109/CDC.2016.7798492												
	Comment: Temperature-driven energy-optimal problem; The system needs to be well-insulated for the heater to be of any assistance.												
	-	Coupled electrothermal model	-20 to 20	LFP	2.3	Cylinder	-	battery	40 °C/ within 150 s	-	The initial SOC is 0.6 and the SOC after warmup is greater than 0.35 to ensure performance after preheating.	-	-
Air preheating + Internal preheating (CV-CC-rest phase)	[91] An energy-optimal warm-up strategy for Li-ion batteries and its approximations. IEEE Transactions on Control Systems Technology, 2018 https://doi.org/10.1109/TCST.2017.2785833												
	Comment: time-limited energy-optimal problem; approximating the optimal policy by either a CV-CC sequence or a CV-CC-rest sequence												
	-	Coupled electrothermal model	-20 to 20	LFP	2.3	Cylinder	-	battery	40 °C/ within 150 s (more loss leads to less warming time)	-	CV-CC trajectory consumes ~9% more energy than CV-CC-rest trajectory	-	-
Electrothermal film preheating + AC	[92] Low Temperature Composite Heating Method for Lithium-ion Power Battery. Chinese Journal of Mechanical Engineering, 2019 (in Chinese)												
	Comment： combined with AC preheating												
	battery connected with a wide wire metal film in series and powered by an AC power supply.	The temperature rising model and equivalent circuit model	-20 to 5	LiMnNiCoO2	3	Cylinder	46	-	0.68 °C/min (only with electrothermal film) 3.2 °C /min	-	1.2 Wh 3.4 Wh	-	-