

Review

Energy Sources and Battery Thermal Energy Management Technologies for Electrical Vehicles: A Technical Comprehensive Review

Sara El Afia ¹, Antonio Cano ¹ , Paul Arévalo ^{1,2,*}  and Francisco Jurado ¹ 

¹ Department of Electrical Engineering, University of Jaen, 23071 Jaen, Spain; se000038@red.ujaen.es (S.E.A.); acano@ujaen.es (A.C.); fjurado@ujaen.es (F.J.)

² Faculty of Engineering, Department of Electrical Engineering, Electronics and Telecommunications (DEET), University of Cuenca, Balzay Campus, Cuenca 010107, Azuay, Ecuador

* Correspondence: warevalo@ujaen.es

Abstract: Electric vehicles are increasingly seen as a viable alternative to conventional combustion-engine vehicles, offering advantages such as lower emissions and enhanced energy efficiency. The critical role of batteries in EVs drives the need for high-performance, cost-effective, and safe solutions, where thermal management is key to ensuring optimal performance and longevity. This study is motivated by the need to address the limitations of current battery thermal management systems (BTMS), particularly the effectiveness of cooling methods in maintaining safe operating temperatures. The hypothesis is that immersion cooling offers superior thermal regulation compared to the widely used indirect liquid cooling approach. Using MATLAB Simulink, this research investigates the dynamic thermal behaviour of three cooling systems, including air cooling, indirect liquid cooling, and immersion cooling, by comparing their performance with an uncooled battery. The results show that immersion cooling outperforms indirect liquid cooling in terms of temperature control and safety, providing a more efficient solution. These findings challenge the existing literature, positioning immersion cooling as the optimal BTMS. The main contribution of this paper lies in its comprehensive evaluation of cooling technologies and its validation of immersion cooling as a superior method for enhancing EV battery performance.



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1. Introduction

The automotive industry has recently emerged as a crucial global sector, notably in terms of its adverse environmental impact. The heavy reliance on fossil fuels not only drives significant air pollution but also contributes massively to greenhouse gas (GHG) emissions, particularly carbon dioxide (CO₂). According to the Environmental Protection Agency (EPA), the transportation industry accounts for approximately 27% of global CO₂ emissions [1]. Additionally, 96% of the world's transportation systems still depend on fossil fuels [2], highlighting the urgent need for cleaner, more sustainable alternatives. Electric vehicles (EVs) have surfaced as a promising solution, capable of reducing emissions significantly by relying on electricity rather than fossil fuels [3].

The rise of EVs is directly linked to a broader global push toward greener transportation solutions that support the goals of reducing GHG emissions and promoting sustainability [4]. While there are various energy storage technologies available for electric vehicles, such as hydrogen fuel cells, ultracapacitors, flywheels, and electrochemical batteries [5], lithium-ion batteries remain the most prevalent and commonly used technology because of their superior energy density and cost-efficiency relative to other technologies. Nevertheless, the limited range of electric vehicles remains a significant disadvantage, typically ranging from 200 to 350 km on a full charge. Batteries are the key and the most

expensive component of an electric vehicle, whereas they are the main obstacle to electric vehicle progression [6]. Thus, the success of these types of vehicles will be largely dependent on the development of better, cheaper, and more powerful batteries [3]. These batteries will increase the autonomy of vehicles. To sum up, the energy storage system is a crucial element of an electric automobile. This storage system must be durable, cost-effective, lightweight, safe, and effective. Batteries generate significant thermal energy during rapid charge and discharge cycles due to various electrochemical reactions and high current levels. This heat generated may cause some serious risks such as overheating or explosion of the car. This means that batteries are extra sensitive to extreme temperatures, experiencing reduced driving range. In order to mitigate this issue, a thermal management system is often used. This system affects overall safety by keeping vehicle components cool and by prolonging component life by avoiding overheating [7]. Therefore, enhancing the sustainability of battery production is crucial for the long-term success of EVs in reducing environmental footprints [8].

Battery performance in electric vehicles (EVs) is intrinsically linked to environmental sustainability, extending beyond production impacts. Inefficiencies in energy storage and thermal management can lead to reduced battery lifespans and increased energy consumption, exacerbating environmental challenges. Therefore, optimizing battery thermal management systems (BTMSs) is essential not only for enhancing performance but also for fostering sustainable practices in EV production. By ensuring that batteries operate within optimal temperature ranges, a BTMS mitigates the risks of overheating and energy waste, thereby promoting longer battery life and reducing replacement frequency, both of which have significant positive implications for the environment.

This paper aims to provide a comprehensive review of current energy storage solutions for electric vehicles, alongside highlighting recent advancements in the field. Specifically, this study focuses on evaluating the effects of elevated temperatures on electric vehicle batteries and emphasizes the critical role of a battery thermal management system (BTMS) in extending battery lifespan. By minimizing the need for frequent replacements and recycling, effective thermal management contributes to resource conservation and the development of more sustainable energy storage systems. To achieve these objectives, this paper systematically reviews the various thermal management techniques used in batteries, assessing their performance across different technologies. In addition, a comparative analysis is performed using MATLAB Simulink software to investigate the dynamic thermal behaviour of BTMS approaches, particularly air cooling, indirect liquid cooling, and immersion cooling.

The novelty of this study lies in its original contribution, providing new insights into the efficiency of a BTMS based on immersion cooling, especially in comparison to indirect liquid cooling systems, which were previously identified in earlier studies as the most efficient method. The analysis reveals that immersion cooling not only outperforms these methods but also offers a simpler and more effective solution for battery temperature regulation. These findings culminate in a significant conclusion that immersion cooling can markedly enhance battery performance and lifespan, establishing it as the most efficient option among the systems evaluated. This contribution presents a fresh perspective and validation in the field of electric vehicle battery thermal management.

This paper's structure is as follows: Section 2 provides an analysis of various electric vehicle technologies and presents the state-of-the-art energy storage and energy generation systems used for electric vehicles. Section 3 analyses the energy management systems for EVs. Section 4 presents an overview of battery thermal management strategies, analysing their advantages, drawbacks, and efficiency. In Section 5, a comparative study and simulations are conducted to assess the impact of different cooling methods, specifically air cooling and liquid cooling, on the performance of lithium-ion batteries using MATLAB Simulink software. And finally, Section 6 presents the conclusions.

2. Electric Vehicle Technology

Electric vehicles are rapidly emerging as a feasible alternative to traditional internal combustion engine cars, delivering a dual advantage of reducing CO₂ emissions and contributing to environmental protection. Among the integral elements within electric vehicles, the battery, known for its susceptibility to temperature fluctuations, becomes a standout concern. In extreme cases, such fluctuations could pose significant safety risks, potentially leading to explosions. This underscores the immediate necessity for the development and integration of efficient battery thermal management systems. Despite the technology's significance, there exists a noticeable gap in comprehensive studies comparing traditional battery thermal management systems with non-cooling battery systems. In this investigation, our primary objective was to scrutinize recent scientific publications assessing the effectiveness of conventional energy sources and battery thermal management systems in electric vehicles. We placed specific emphasis on academic and research databases renowned for their expertise in this domain. The primary objective of this research was to evaluate the dynamic thermal performance of different conventional cooling systems, such as air cooling, direct liquid cooling, and immersion cooling. Our aim was to identify the most efficient system while also acknowledging the limitations and weaknesses inherent in each technology.

Electric vehicles (EVs) are forms of transportation that use electric motors to move forward, rather than internal combustion engines. The basic components of the electric vehicle type are a power source, power converter, electric engine, and mechanical gearbox, as shown in Figure 1.

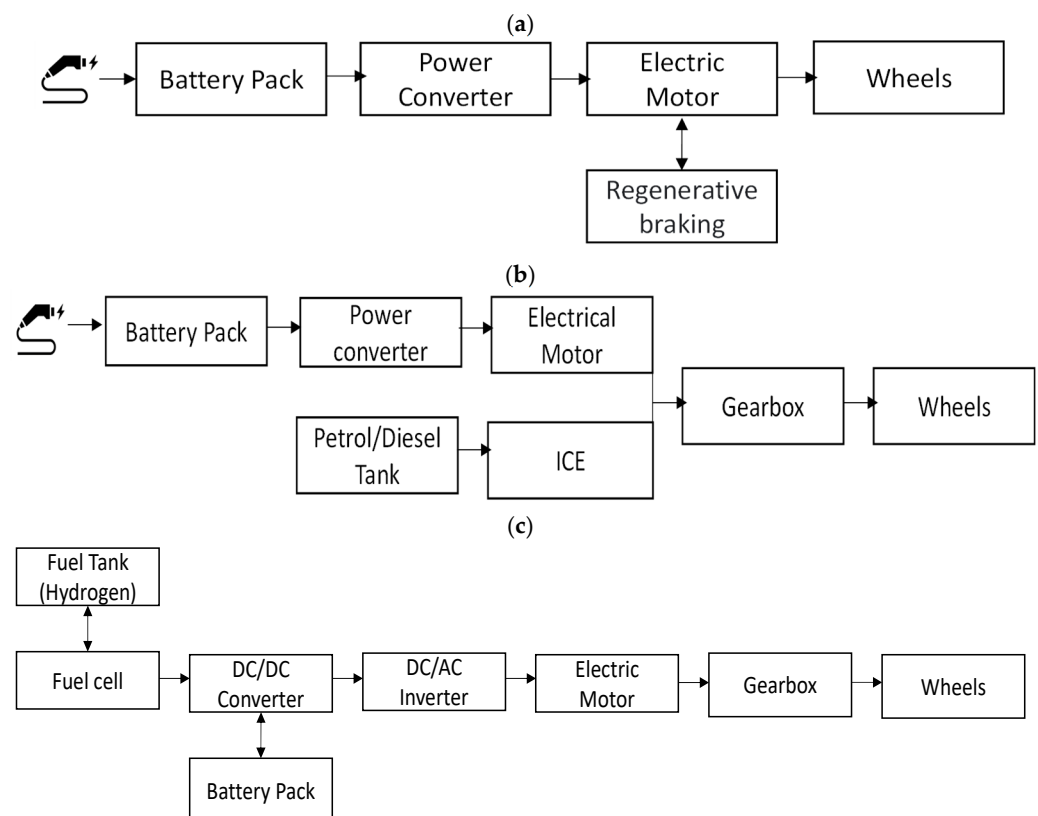


Figure 1. Basic layout of EV systems: (a) battery electric vehicle (BEV); (b) plug-in hybrid electric vehicle (PHEV); and (c) fuel cell electric vehicle (FCEV).

Unlike internal combustion engine automobiles, electric vehicles do not generate exhaust emissions while operating. As a result, electric cars are more beneficial to the environment than conventional automobiles. Additionally, sustainable resources like wind, solar, or biogas power plants can be employed to supply the necessary electrical energy for

recharging the vehicle. As a result, the vehicle's overall efficiency will increase, and fuel consumption will be reduced. Besides that, electric cars may be divided into four distinct categories as follows:

- Battery electric vehicles that operate completely on electricity.
- Plug-in hybrid electric vehicles are automobiles equipped with both a conventional combustion engine and an electric motor, powered by an external electrical source.
- Hybrid electric cars that combine the power of an electric motor with that of a traditional internal combustion engine.
- Fuel cell electric cars use an electric drivetrain that operates with a combination of compressed hydrogen and oxygen.

Electric vehicles are an interesting solution, especially in that they offer advantages such as zero emissions, simplicity, low cost, and efficiency [1]. But, on the other hand, the main disadvantages are the range, which reaches 350 km in an electric vehicle, the charging time, which can take 4 to 8 h for a full charging of the battery unit, and the cost of batteries, which is expensive. Lastly, the battery is highly sensitive to extreme temperatures, which can lead to overheating or even car explosions [1].

There are four principal factors affecting electric vehicle adoption. The first is charging operation, such as the charging time being very high, and the lack of public chargers. The second is low investment profitability. The third is that consumers are afraid to change to new transport technology despite promoting policies. The fourth is the persistent concern regarding battery thermal issues.

2.1. Energy Sources for Electric Vehicles

The viable energy sources proposed for EVs include batteries, fuel cells, capacitors, and flywheels. Among them, batteries, capacitors, and flywheels are energy storage systems in which electrical energy is stored during charging, whereas fuel cells are energy generation systems in which electricity is generated by chemical reactions. Among these, batteries are the foremost commonly used energy storage solution for electric vehicles. On the other hand, the energy generation system pertains to the process of producing electricity to charge the energy storage unit of an electric vehicle. This process involves the conversion of different forms of energy, such as chemical or solar energy, into electrical energy.

2.1.1. Hydrogen Fuel Cells

Hydrogen contains abundant energy per unit of weight but produces little energy per unit of volume, which is a major drawback for transportation. A hydrogen fuel cell is a type of electrochemical cell that transforms chemical energy into electrical energy by using hydrogen and oxygen. This system consists of an anode, which is where the hydrogen goes, a cathode, where the oxygen goes, and an electrolyte, which is often potassium hydroxide [9]. The main advantages of this technology are its higher efficiency (80%) and environmentally friendly nature; fuel cells are also significantly lighter and more compact [10]. However, the two main drawbacks of fuel cell technology are the substantial initial expense and the limited lifespan. The solid polymer fuel cell (SPFC) has the advantages of the highest power density among all fuel cells, solid electrolytes with no corrosive liquid in the cell, and insensitivity to carbon dioxide in the oxidant. At present, the major challenge is how to significantly reduce the material cost of the solid polymer membrane and platinum-catalysed electrodes. Figure 2 shows a schematic of a fuel cell.

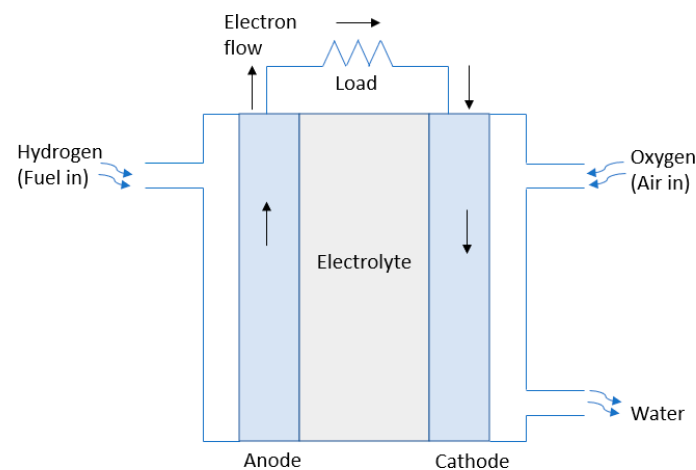


Figure 2. Schematic of a fuel cell based on hydrogen.

2.1.2. Solar-Powered Vehicles

The solar cells within the vehicle's structure absorb the radiation from sunlight and convert it into electrical energy. Currently, the leading manufacturing PV technologies on the market are crystalline silicon PV and thin-film PV. This electricity is then stored in an accumulator or battery for later use. Additionally, solar panels are integrated into the roof of the vehicle to maximize the harvesting of solar power and enhance the overall efficiency of the solar power generation process. Solar vehicles possess several advantages such as utilizing renewable energy, reducing dependence on fossil fuels, and minimizing environmental harm. However, the main drawbacks of this technology are the limited driving range and dependency on sunlight availability, which can pose significant challenges, particularly for long-distance travel or in regions with cloudy or rainy weather conditions [11,12].

On the other hand, energy storage pertains to an electric vehicle's capacity to retain electrical energy within an energy storage system. The stored energy is subsequently used to power the vehicle's electric motor. The energy storage technology allows the electric car to run without requiring a continuous external power supply. Nowadays, energy storage is increasingly becoming a vital element in the progress of electric vehicles. Energy storage technologies are methods that store energy in an easily usable form at off-peak demand periods to use it at peak period demand [13]. However, energy storage capacity is the main weakness of the development of EVs. The latter must elaborate a powerful energy storage system boasting both high specific energy and outstanding specific power. Electrochemical batteries are the most commonly utilized technology for electric vehicles. In addition, the principal types of this technology are lead–acid, nickel–metal hydride, nickel–cadmium, solid-state, and lithium-ion batteries. The fundamental characteristics of electrochemical batteries are their high specific energy, long cycle life, and lower price [14]. The second category of energy storage includes electrostatic storage using ultracapacitors and mechanical storage using flywheels [14]. Overall, the energy source systems used in electric vehicle applications can be classified into flywheel, ultracapacitors, and electrochemical batteries [15].

2.1.3. Flywheel Energy Storage

Flywheel energy storage or FES is a storage device that stores/maintains kinetic energy through a rotor/flywheel rotation. It consists of a carbon fibre wheel, floating magnet, generator or motor, and power electronic control system. The traditional flywheel is a massive steel rotor with hundreds of kg that spins at hundreds of radians per second. On the contrary, the advanced flywheel is a lightweight composite rotor with tens of kilograms and rotates at thousands of radians per second, the so-called ultrahigh-speed flywheel. As a result, it uses the same motor/generator to transform kinetic energy into electric energy

and vice versa [3]. The advantages of flywheel batteries include a specific energy level of approximately 40 Wh/kg, with a specific power exceeding 3000 W/kg, no gas emission, a long life cycle, and flexibility in design and operation. The biggest challenges of this technology are the high cost and the self-discharge risk [1].

The flywheel system has been used in conjunction with other powertrain technologies rather than as a stand-alone propulsion system [16]. Flywheels can improve electric vehicle energy economy and performance by acting as a secondary power source, delivering short bursts of energy during acceleration or regenerative braking as Figure 3 shows. As a result, they contribute to an overall improvement in the vehicle's efficiency and performance [3].

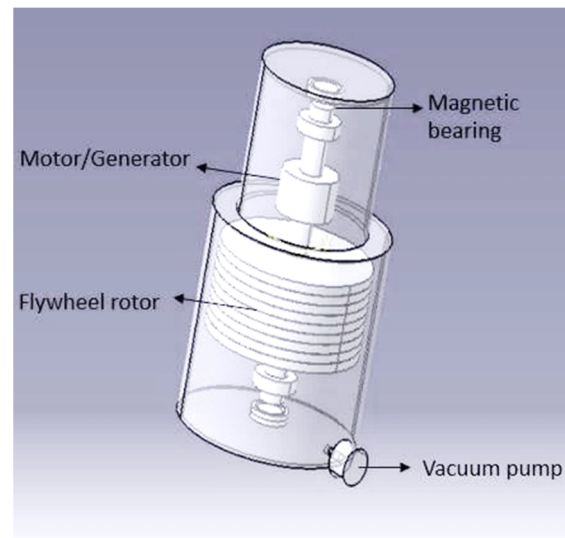


Figure 3. Flywheel energy storage system.

2.1.4. Ultracapacitor

An ultracapacitor is a type of energy storage device that can store massive amounts of electrical charge and recharge very quickly. Typically, an ultracapacitor consists of electrodes composed of activated carbon, aluminium current collectors, and potassium hydroxide electrolyte solution. Expensive cost, restricted energy density, rapid self-discharge, and diminished cell voltage are generally considered to be this technology's biggest weaknesses [17,18]. Ultracapacitors are extensively used in electric vehicles with other energy storage technologies such as batteries. The merging of ultracapacitors with batteries allows electric vehicles to benefit from ultracapacitors' higher power output and efficiency while relying on batteries for increased energy storage and longer driving range. Figure 4 shows an ultracapacitor systems.

2.1.5. Batteries

Electrochemical storage systems or batteries are currently the most commonly employed energy storage solution for electric vehicles. In general, this system uses a reversible process to convert chemical energy into electrical energy and vice versa. This technology has two roles; the first is to store electrical energy and the second is to release it via the process of charging and discharging. Rechargeable batteries hold a dominant position in the market for energy storage systems in electric vehicles [13]. A battery consists of a group of electrochemical accumulators, each accumulator consisting of an anode, a cathode, an electrolyte and a separator [9].

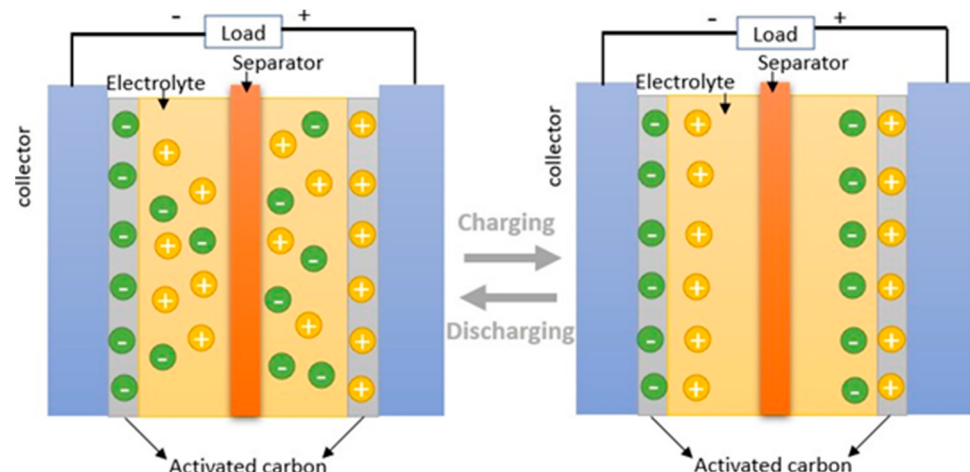


Figure 4. Diagram of the structure of the ultracapacitor system.

Each battery has both positive and negative terminals that connect to a charger or load. The positive terminal frequently consists of aluminium, whereas the negative terminal is made of copper. The electrodes are critical in determining the density and capacity of the battery [19]. Currently, the most commonly used batteries in electric vehicles are lithium-ion, lead–acid, and nickel–metal hydride. These battery technologies offer several advantageous characteristics, including high energy density, low self-discharge rates, and a wide operating temperature range [20,21].

- Lead–acid batteries

Lead–acid (LA) is considered the oldest battery technology of electric vehicles. This configuration consists of lead (Pb) serving as the anode, lead dioxide (PbO₂) as the cathode, and sulfuric acid (H₂SO₄) as the electrolyte [17]. It is distinguished by its cheapness and simplicity. It uses metallic lead for the negative electrode, lead dioxide for the positive electrode, and sulfuric acid solution for the electrolyte. In general, the LA battery has a cycle life of around 700, a specific energy of approximately 35 Wh/kg, and a specific power of approximately 150 W/kg. Limited specific energy and a low life cycle are the main drawbacks of LA batteries [18]. Thus, this battery type will never be the best option for a reliable electric vehicle. Despite those drawbacks, the cost of this battery is cheaper than other energy storage alternatives.

- Nickel-based batteries

Ni-MH batteries are made of nickel hydroxide as the cathode, alloys that absorb hydrogen serving as the anode, and potassium hydroxide employed as the electrolyte [22]. Its active materials are metallic cadmium for the negative electrode, nickel oxyhydroxide for the positive electrode, and potassium hydroxide solution for the electrolyte. Ni-MH batteries have a lifespan of around 1500 cycles, a specific energy of roughly 70 Wh/kg, and a specific power of approximately 200 W/kg [9]. The biggest issues with this battery are its hefty price, heavy weight, and high self-discharge rate [22]. On the other hand, NI-MH has a long life cycle, a wide temperature range, and significant specific energy.

- Lithium-ion batteries

A lithium-ion battery is a rechargeable type of battery that consists of an anode made of carbon, a cathode that is often composed of a metal oxide, and a lithium salt as the electrolyte [23]. Currently, the majority of electric vehicles use lithium-ion batteries because of their compact size, light weight, and low memory effect [15]. Al Shdaifat et al. [19] explain that the Li-ion battery is gaining prominence as a battery technology for electric vehicle applications, primarily due to the utilization of lithium, which boasts the lightest atomic mass and the highest negative potential among elements. Equivalently, these ions swing through the electrolyte between the negative and positive electrodes, and no

metallic lithium is deposited. A lithium-ion battery provides electric vehicles with superior performance attributes concerning range and acceleration. In addition to the elevated specific energy offered by Li-ion batteries, they also exhibit remarkable durability and longevity. Moreover, Li-ion batteries feature a conventional design and operate at elevated voltage levels, further enhancing their overall efficiency and effectiveness [24]. Lithium-ion battery provides the highest energy density and extended lifespan compared to alternative battery technologies. According to Osmani et al. [25], lithium-ion batteries demonstrate the highest level (approximately 95%) in terms of energy efficiency, allowing for discharge rates of up to 100%. Moreover, lithium-ion batteries exhibit a low self-discharge rate and rapid charging, and they boast various other enhanced performance characteristics, rendering them highly appealing.

On the other hand, the major weaknesses of lithium-ion batteries in electric cars are their high cost, their need for protection from becoming overcharged, and their sensitivity to high temperatures, which requires an effective system for managing battery thermal conditions to guarantee the secure and dependable functioning of the device [20]. Figure 5 shows a lithium-ion battery schematic.

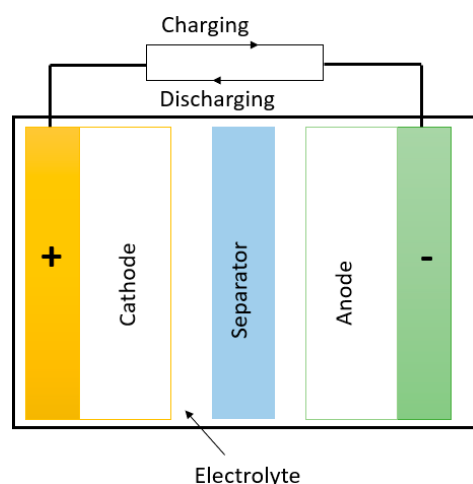


Figure 5. Diagram illustrating the process of charging and discharging in a lithium-ion battery.

- Solid-state batteries

Solid-state batteries have been widely regarded as a promising electrochemical energy storage technology to power electric vehicles (EVs) that raise battery safety and energy/power densities as kernel metrics to achieve high-safety, long-range, and fast-charge operations. Unlike lithium-ion batteries, these systems utilize solid electrolytes instead of liquid electrolytes [26]. The solid electrolyte conducts ions between the anode and cathode, which helps to prevent the formation of dendrites that can lead to short circuits [26]. In research and development, numerous solid-state electrolytes have been developed for solid-state batteries. The first category includes solid oxide electrolytes, which encompass NASICON, perovskite, garnet, Li_3PO_4 , and amorphous/glass electrolytes. The second category comprises solid sulphide electrolytes, which consist of Li_2S - SiS_2 -based electrolytes, Li_2S - P_2S_5 -based electrolytes, and $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ electrolytes. Finally, the third category includes solid polymer electrolytes, which comprise polyethylene oxide (PEO)–salt systems, single Li-ion conducting (SLIC) solid polymer electrolytes, and non-polyether-based electrolytes [27].

Thus, the main advantages of solid-state batteries include high energy density, compactness, and enhanced safety compared to lithium-ion batteries [28]. However, solid-state batteries continue to face challenges such as interfacial ion transport mechanisms, reduced storage capacity, ionic conductivity, and limited lifespan. Moreover, they also incur higher manufacturing costs compared to lithium-ion batteries. Further, efforts are underway to refine the overall functionality, efficiency, and capabilities of solid-state batteries. Hence,

this technology is presently in the research and development phase [28]. Figure 6 shows a schematic of the solid-state battery.

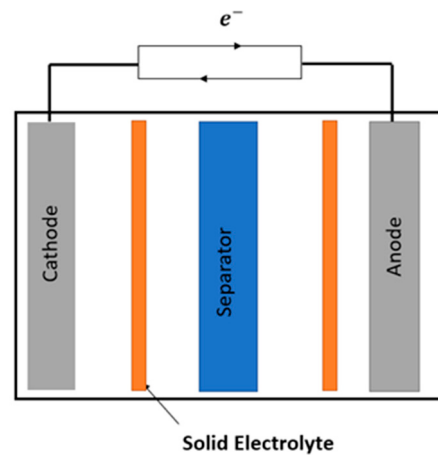


Figure 6. Schematic of the process of a solid-state battery.

Table 1 displays a comparison of different energy sources utilized in electric vehicles. According to the literature and Table 1, lithium-ion batteries offer a lot of potential and benefits compared to alternative energy storage technologies, such as high specific energy, excellent energy density, limited self-discharge, and lengthy lifespan. Because of their advanced qualities, lithium-ion batteries are recommended for electric vehicles [20]. In the upcoming sections, the studies and systems discussed will solely focus on lithium-ion batteries.

Table 1. Typical characteristics of EV energy storage systems.

Categories of Energy Storage	Energy Storage System	Specific Power W/kg	Energy Density Wh/L	Lifespan	Cost USD/kWh	EV Model	Strengths	Weaknesses
Electrochemical systems	Lead-acid [9,13,17]	200–400	60–100	2000–4500	120–150	GM EV1	Good specific power, established technology, and low cost	Limited cycle life, low energy density, and expensive maintenance
	Ni-MH [9,13,22]	150–300	100–140	500–3000	150–200	Honda EV Plus	Higher specific energy and high temperature range	High cost and severe self-discharge rate
	Li-ion [13,15,20,23]	500–2000	240–280	1500–4500	150–1300	Tesla Model (S, Y) Nissan Leaf BMW i3 Porsche Taycan	Elevated energy density, high voltage operation, no memory effect, lighter, low self-discharge, and long life cycle	Costly, safety issues, and fragile
	Solid-state [26,28]	300–500	500–700	-	500–700	Under development	High energy density, compact size, and absence of thermal issues	High manufacturing cost and developing technology
electro-mechanical system	Flywheel [1,3,22]	3000	-	10 ⁵	10,000	-	Short recharge time and environmentally friendly	High cost, less mature technology, and short discharge
Electrical system	Ultracapacitor [11,17]	500	-	10 ⁶	10,000	-	Long life cycle, high energy density, and fast charge and discharge	High cost, and need protection from over-charging
Hydrogen-based storage	Fuel cell [9,10,29]	2000	770	-	-	Toyota Mirai	Low emission, compact, provides continuous power, safe	High capital investment and hydrogen storage and transportation

3. Energy Management Systems for EVs

An energy management system is defined as a solution that controls a battery's operation via electronic and mechanical systems. To guarantee both the safety and prolonged operational lifespan of the battery, energy management systems are essential in electric vehicles [30]. That is to say, this system measures and analyses the flaws in the energy distribution and storage systems of electric vehicles. Therefore, all separate modules and their functioning are managed by this central control system.

Energy management strategies can be classified into electrical management, thermal management, and safety management [31]. The main function of an electrical management system is to regulate the charging voltage and current, based on the battery's characteristics (such as SOC. . .), for the purpose of avoiding imbalanced cells in the charging and discharging processes. A thermal management system is a system that keeps an EV's components at the optimum temperature to minimize power losses. On the other hand, when an EV's elements are in a high-risk condition, the safety management system is utilized to rectify the evaluation of sensor outputs and shut them down. Figure 7 shows the control unit of the EMS.

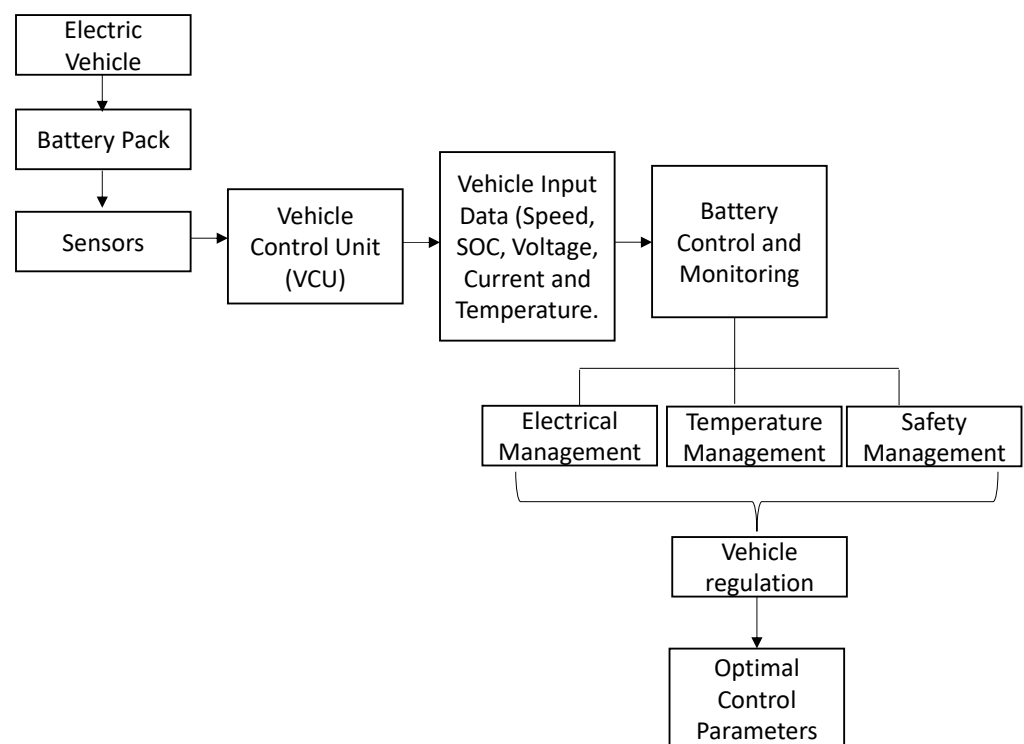


Figure 7. Overview of the energy management system (EMS).

To summarize, to guarantee battery safety and dependability, it is important to check the temperature, voltage, and current of the batteries and to accurately estimate their states in real time. Moving forward, the next section will focus specifically on the battery thermal management system for electric automobiles, examining the unique challenges and innovative solutions in this area. Figure 7 shows an energy management system schematic.

3.1. Battery Temperature Impacts and Heat Generation in EVs

At present, Li-ion batteries function as the most effective power source in electric vehicles. Due to their elevated energy and power densities, lithium-ion batteries provide a large capacity and excellent operating qualities. Nevertheless, the effectiveness of Li-ion batteries is severely impacted by temperature, which is a critical factor [32].

Temperature Effects on an EV's Battery

Temperature effects play a critical role in ensuring the appropriate management of batteries. According to [33], Li-ion batteries have a lifespan of 3323 cycles at 45 °C, which reduces to 1037 cycles at 60 °C. This indicates that the battery's cycle life and energy capacity are heavily impacted by temperature. Aguemont et al. [34] explain that at low temperatures, a Li-ion battery's electrolyte becomes more viscous, which decreases its ionic conductivity and raises the battery pack's internal resistance. In contrast, at high temperatures, battery self-discharge appears while the battery capacity begins to degrade. Moreover, high temperatures increase heat generation inside the battery, accelerate thermal ageing, and reduce the cycle life of battery cells [34]. Figure 8 shows the temperature on the charging and discharging of a Li-ion battery cell.

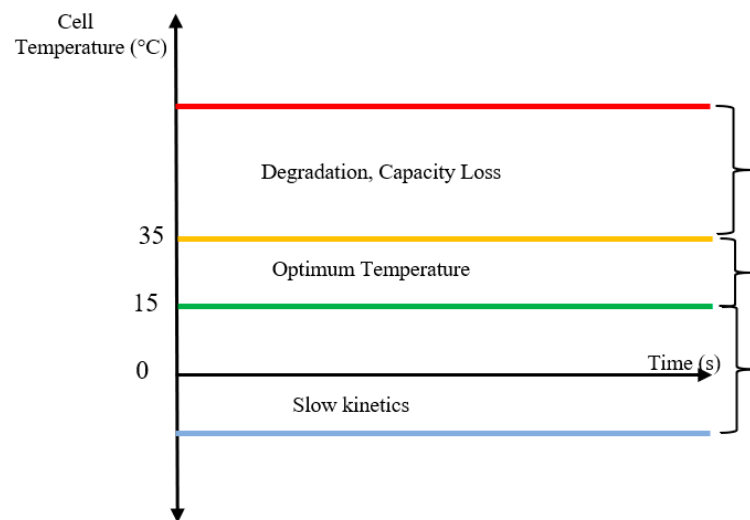


Figure 8. The influence of temperature on the charging and discharging of a Li-ion battery cell [34].

4. Thermal Management System for Batteries in Electric Vehicles

The effectiveness of electric vehicle technologies primarily relies on battery efficiency. A battery's power capacity and life cycle are more significant in this regard [35]. Z. Rao et al. [36] emphasize that battery safety is a significant obstacle to the development of electric automobiles. Throughout various electrochemical reactions and at high current levels, batteries produce a significant amount of heat energy when undergoing fast charging and discharging processes. This heat generated may cause some serious risks such as overheating or explosion. Furthermore, under extreme temperature rise, the battery life cycle is significantly reduced [36].

In contrast, J. Li et al. [37] explain that there exists a direct correlation between battery cell temperatures and chemical reaction rates. Thus, a significant temperature drop will directly reduce the reaction rate and, consequently, it will negatively impact the battery's current carrying capacity. That is to say, the cell battery power capacity will be decreased. On the other hand, a high temperature increases the chemical reaction rate; consequently, it increases the thermal energy dissipation, which results in a thermal runaway. This means that battery electric vehicles are hypersensitive to extreme temperatures, which reduces their driving range.

According to R. Matthe et al. [38], EV batteries attain optimum efficiency when their temperature range is between 15 and 35 °C. Thus, temperature should be maintained in this range to guarantee the performance of batteries. Consequently, this problem requires an effective thermal energy management system. This system allows batteries to operate safely and efficiently and extends their life cycle by managing the heat generated [7]. That is to say, a thermal management system affects an electric vehicle's overall safety by keeping all components cool, providing the optimal temperature for passengers, and prolonging component life by avoiding overheating. Figure 9 shows the control unit of the TMS.

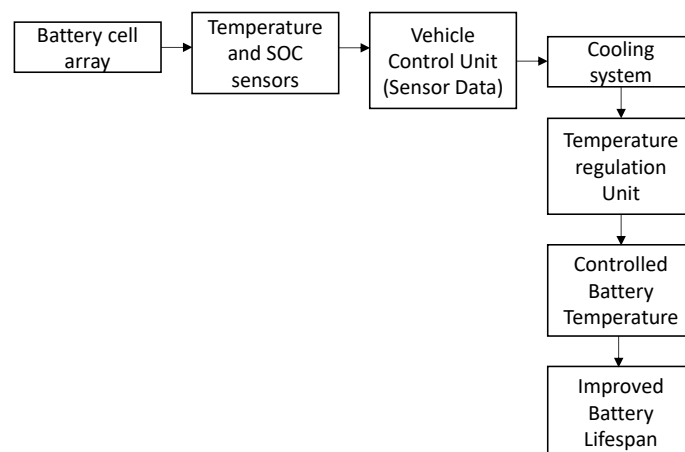


Figure 9. Thermal management system (TMS) for electric vehicles.

As stated by Li et al. [39], the detrimental consequences of thermal runaway can lead to the disintegration of a battery's components caused by interactions between the positive and negative electrodes. On the other hand, according to Xu et al. [40], for a Li-ion battery pack, if thermal runaway initiates in one battery cell, the heat readily spreads to neighbouring battery cells, leading to the propagation of thermal runaway. This has the potential to trigger a fire throughout the entire lithium-ion battery pack, leading to the car's fiery explosion.

The battery thermal management system represents a comprehensive technological solution designed to regulate the temperature range within which electric vehicle batteries operate, thereby preventing thermal runaway [41]. According to the research by Pesaran [42], this technology should consist of four necessary functions, which are cooling, heating, insulation, and ventilation. The cooling function is required because, during charging operation, battery cells do not generate only electric energy but also heat, which negatively affects the battery's performance. Ventilation is necessary to eliminate potentially hazardous gases within the battery pack. Insulation is a crucial function that reduces heat transfer between the battery's interior and exterior and enhances safety, particularly in hotter or colder climates. In colder regions, the heating function becomes essential to assist the battery pack in reaching the suitable temperature range.

4.1. Classification of Battery Thermal Energy Management Systems for Electric Vehicles

Battery thermal management technology includes two essential functions: cooling and heating. However, most of the previous research considered cooling BTMSs. In contrast, only a limited number of studies have addressed the function of heating technology, possibly due to the heat generated by battery cells during chemical reactions [12]. The three types of heating technologies are self-heating, external heating, and pulse heating, according to [19]. Therefore, the cooling function is more critical than the heating function. Figure 10 shows a schematic of the battery thermal management.

According to Ruochong Li [43], traditional battery thermal management systems can be classified into three primary categories: air cooling, liquid cooling, and the application of phase change materials (PCMs) for cooling. These technologies can be separated based on their performance, cost, size, and response time. Furthermore, the categorization of a BTMS is dependent mainly on the cells' arrangement within the battery pack, energy usage, thermal transfer fluid, and the interaction between the coolant and battery surface.

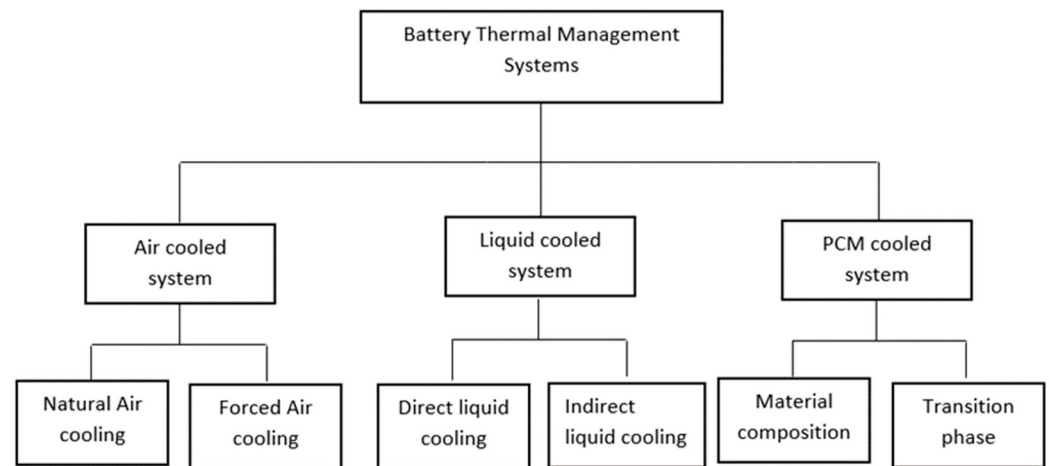


Figure 10. Overview of battery thermal management methods.

4.1.1. Air-Cooled BTMSs

Battery cooling systems utilizing air can be divided into two main categories: natural air cooling and forced convection cooling. The natural air cooling system uses ambient air as a cooling medium to remove the heat produced during battery operation. This method utilizes only the natural convection of air to dissipate heat from the battery, with no additional cooling devices.

On the other hand, forced air BTMSs represent a technique employing air as the heat transfer medium; the airflow used for cooling can be generated by a fan. The fundamental working principle of this approach is to let air traverse the battery module to remove or bring the heat for the purpose of holding the battery temperature in the optimum range (heat dissipation or heating) [44,45]. Air cooling systems use fans to circulate cool air into the BTMS and exhaust hot air to the exterior. This approach is the most commonly adopted BTMS cooling system since it is inexpensive and simple to install. Moreover, the principal advantages of forced air BTMSs are lightweight, low maintenance cost, simplicity, and less energy consumption [37,44]. Wang et al. [29] developed a model to forecast the thermal behaviour of batteries during discharge, both with and without the use of air cooling. Their findings show that air cooling is not necessary when the discharge rate is under 3 °C and the surrounding temperature is below 20 °C. However, when the ambient temperature exceeds 35 °C, air cooling becomes less effective, and significantly more fan power is required to maintain the system's temperature within a safe range.

As per reference [39], the arrangement of the battery pack, including aspects such as how the battery cells are positioned, how they are connected, and the spacing between them, affects the global performance of a BTMS based on the air cooling system. Yang et al. [46] investigated how two prevalent setups, staggered and aligned configurations, affected the efficiency of an active BTMS using forced air cooling. The study revealed that the staggered design leads to a reduced maximum temperature variation in the battery. Fan et al. [47] pointed out that the thermal distribution is impacted by irregular gap spacing, although it does not have a substantial effect on the increase in the maximal temperature.

4.1.2. Liquid-Cooled BTMSs (Direct and Indirect System)

A liquid-cooled BTMS is a technology that uses liquid as a thermal medium to convey heat and to achieve the desired thermal effects. Battery thermal management technologies based on liquid cooling can be categorized into two primary divisions: indirect liquid cooling and immersion cooling systems.

An indirect liquid cooling system operates by circulating a transfer fluid, such as water or a mixture of ethylene glycol, through a network of pipes positioned in close proximity to the batteries [44]. The heat generated by the batteries is transferred to the coolant through

cooling modules via conduction. The heated fluid is then pumped away from the batteries to a heat exchanger, where the heat is released to the surroundings [44,48].

The indirect liquid cooling system offers several key advantages. Firstly, it ensures efficient and uniform cooling throughout the battery pack, reducing temperature variations and maintaining consistent performance. Additionally, this cooling method effectively disperses heat, preventing overheating and enhancing overall system reliability. Furthermore, by providing insulation between the batteries and the coolant, this cooling system significantly improves safety by minimizing the risks of leakage or direct exposure to potentially harmful substances [34,48]. However, there are some notable drawbacks to this technology. Firstly, the implementation of the system can be complicated and costly because it requires multiple components and incurs higher installation expenses. Furthermore, these additional components occupy valuable space and contribute to the overall weight of the battery system [34,49].

The second liquid cooling approach is direct contact cooling, also known as immersion cooling, where the battery cells come into direct contact with a cooling fluid. This means that the battery cells can be submerged directly in liquids like hydrocarbon oils, silicone oils, and fluorinated hydrocarbons [50]. On the other hand, the properties of the cooling fluid are crucial for achieving maximum efficiency and maintaining thermal stability in immersion cooling systems. When selecting immersion cooling fluids, several important criteria need to be met. Initially, it is essential for the fluids to exhibit characteristics of electrical insulation in order to hinder the transfer of electrons between the battery and the fluid, thereby mitigating any possible concerns related to electronic leakage. Moreover, the fluid should display a considerable capacity for specific heat and thermal conductivity. Additionally, it is vital to use nonflammable fluids to ensure safe operation and minimize the risk of fire in case of a battery thermal runaway. Moreover, the ideal fluid should be easily accessible in significant quantities, particularly for the mass production of electric vehicles. Furthermore, the fluid for immersion cooling should possess a suitable range of operating temperatures, a prolonged lifespan, lightweight characteristics, low viscosity, and an environmentally sustainable composition [50].

In recent years, immersion cooling has gained significant attention in EV development as one of the emerging cooling technologies [51]. Many research investigations have been carried out to assess the efficiency of this groundbreaking technology. Park et al. [52] highlighted the importance of considering specific design factors when selecting a BTMS, including module width, gap size, coolant flow rates, and anticipated battery load. They observed that a slim battery module with reduced gaps required less parasitic power when compared to a broader module with larger gaps. This outcome can be attributed to the lower coolant flow rates in the narrower modules. Furthermore, they found that wider modules with larger gaps exhibited reduced temperature variations between cells. The study also indicated that air cooling required a higher amount of parasitic power when contrasted with liquid immersion cooling, particularly under high battery loads. Consequently, liquid immersion cooling may prove to be more energy-efficient for managing heat dissipation in demanding scenarios.

Nelson et al. [53] conducted a study where they employed a thermal model to examine a system comprising 48 cells. They compared the effectiveness of direct cooling utilizing silicone oil to that of an air-cooling system. The results indicated that utilizing this fluid for immersion cooling displayed remarkable heat dispersion, as indicated by a mere 2.5 °C increase in cell temperature under identical load conditions. In contrast, air cooling led to a temperature rise of 5.3 °C.

T. An [11] studied cooling methods for a 50 V lithium-ion battery pack with 14 pouch cells, including natural convection and various dielectric fluid immersion techniques. Their research showed that using flowing dielectric fluid with tab cooling was notably more effective, lowering the maximum temperature at the positive tab by 46.8% compared to natural convection at a 3C discharge rate.

Diahovchenko et al. [12] explored the thermal management efficiency of an immersion cooling setup utilizing FS49 dielectric fluid for an 18,650 lithium-ion battery pack housed in a polycarbonate enclosure, focusing on its performance under rapid charging scenarios. The investigation revealed that the immersion technology exhibited remarkable heat dissipation capabilities, surpassing forced air cooling. Specifically, it reduced peak temperatures by 7.7 °C during 2C charging and 19.6 °C during 3C charging. Moreover, the energy consumption for cooling with the immersion system was notably lower than that of forced air cooling, registering only 14.41% and 40.37% during 2C and 3C charging, respectively.

M. Yacoub et al. [19] conducted a comprehensive study on an oil-immersed battery cooling system, comprising 16 lithium-ion batteries, to optimize heat dissipation and temperature uniformity. By employing mineral oil as the coolant, they investigated the impact of battery spacing and coolant flow rates on the system's thermal performance. The results demonstrated that strategically adjusting battery spacing and increasing coolant flow rates were crucial in minimizing the maximum temperature rise and achieving uniform temperature distribution across the battery module.

In essence, the immersion cooling system functions by submerging the battery pack within a special fluid to efficiently control its temperature. This technique helps maintain the battery pack within an optimal temperature range, resulting in enhanced battery lifespan and improved performance of electric vehicles. Immersion cooling has emerged as a promising solution for efficiently cooling high-capacity EV batteries, offering advantages such as improved thermal efficiency and reduced weight and complexity compared to conventional cooling systems.

Nevertheless, widespread industrial implementation of immersion-cooled systems has been limited thus far due to various challenges. These challenges include concerns about the cost of cooling fluids and uncertainties surrounding the long-term benefits of the system. However, there are notable instances of immersion cooling being adopted in specific EV industrial applications [50]. For instance, Kreisel makes use of Shell's thermal liquids, Xing Mobility incorporates 3M's Novec fluid, and Rimac Automobile opts for Solvay's Galden fluids. These cases serve as evidence that some EV manufacturers are gradually embracing immersion cooling technology, highlighting its potential and stimulating further exploration in the industry [50].

4.1.3. BTMSs Based on PCM

This technology is a passive system that uses phase change materials (PCMs). These materials store, release, and absorb energy in order to supply heat or cooling during phase transition. For BTMSs, the main purpose of PCMs is to transfer heat from a vehicle's battery to outer space. Therefore, it should protect the battery pack from overcharging and over-discharging to prevent the battery pack from exploding and damage [54]. The three basic types of materials that can be used in this technology are organic materials (organic acids), inorganic substances (salt hydrates), and eutectic mixtures [44]. Overall, a BTMS based on PCMs is a highly efficient technique that controls temperature fluctuations and avoids thermal runaway. Therefore, it possesses several advantages, such as excellent temperature consistency, efficient energy utilization, and cost-effective operation [54]. Figure 11 shows a schematic of the battery thermal management systems.

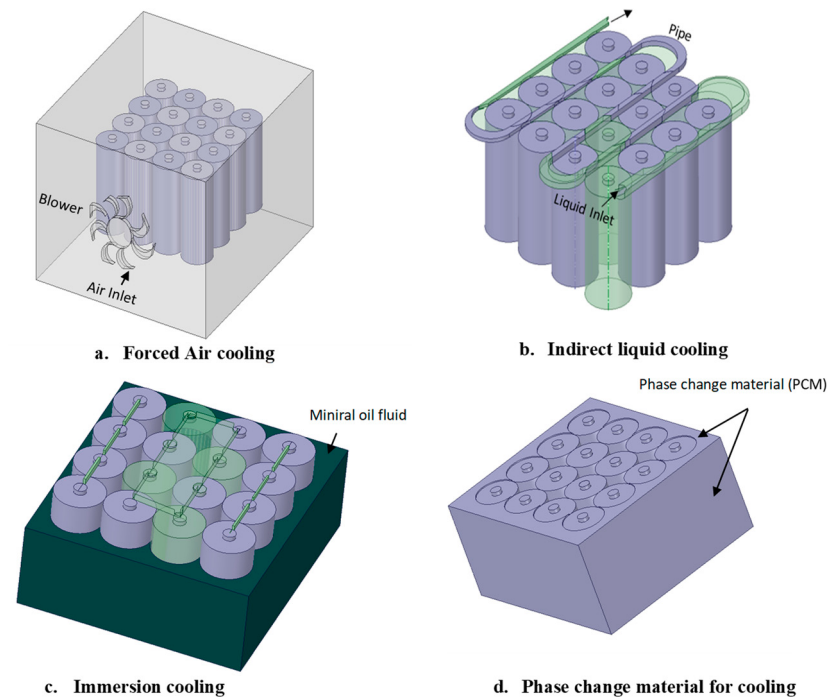


Figure 11. Basic layout and design of various battery thermal management systems.

5. Evaluation of Various Battery Thermal Management Systems for Electric Vehicles: A Case Analysis

In this section, we study the modelling and configuration of the battery thermal management system, specifically addressing various cooling systems, with a focus on air cooling and liquid cooling. In order to simulate the dynamic thermal behaviour of a Li-ion battery pack, we employed MATLAB Simulink to model and analyse the temperature variations within the battery system over time [55].

5.1. System Description

The BTMS analysed in this study consists of three key components: the battery pack, cooling mechanisms (air cooling, indirect liquid cooling, or immersion cooling), and a temperature control system. Figure 12 shows the investigated battery pack consisting of 12 identical lithium-ion cells connected in series, each at 3.2 V and 2.9 Ah, as outlined in Table 2. The cells are of a tabulated design, incorporating thermal ports and state of charge (SOC) monitoring capabilities. This configuration enables accurate thermal tracking during the simulation, ensuring precise modelling of cell behaviour under various thermal conditions and cooling strategies.

Table 2. Basic parameters of the Li-ion battery.

Parameter	Value
Cell type	1865
Voltage (V)	3.2
Capacity (Ah)	2.9
Discharge cycle life	300

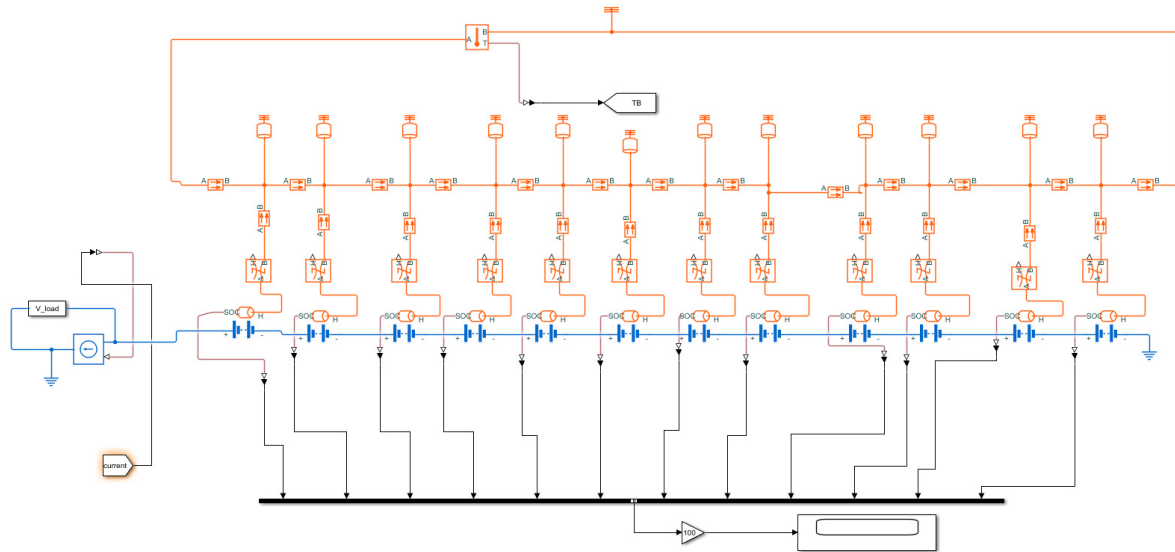


Figure 12. Battery pack configuration using Simulink.

In this study, the thermal performance of a lithium-ion battery pack is evaluated under various cooling strategies, including forced air cooling, indirect liquid cooling, and immersion cooling, in comparison to a passive cooling system. Four cooling system models are developed using MATLAB Simulink to assess the thermal behaviour of each cooling method.

The first simulation model (Figure 13) assessed the thermal performance of a lithium-ion battery pack in the absence of cooling systems while integrating temperature sensors as crucial components. The main goal is to achieve a comprehensive understanding of how temperature changes within the battery pack occur under various environmental conditions, with an emphasis on the critical role played by a battery thermal management system in controlling temperature increases within the battery pack.

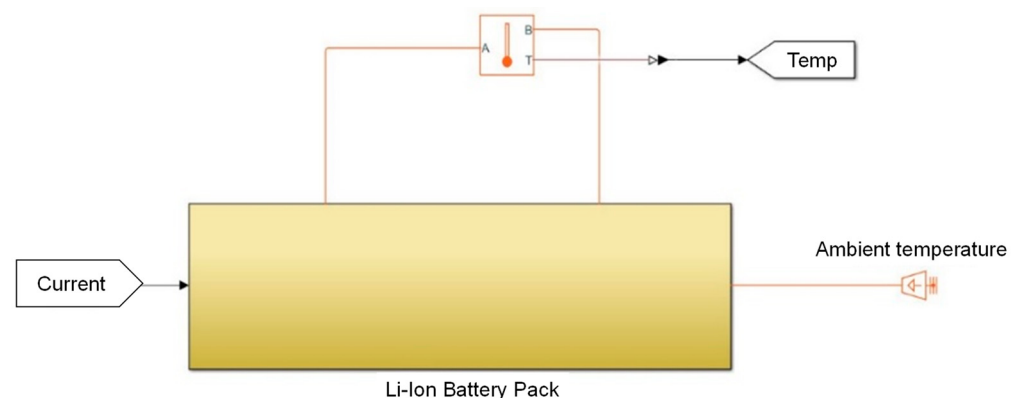


Figure 13. Simulation of a lithium battery without a cooling system.

The second simulation (Figure 14) involves the battery thermal management system utilizing air cooling technology. In this setup, a blower is employed to facilitate the circulation of air within the battery. A temperature sensor is used in this system to continuously track the battery's heat output. In order to dissipate heat and keep the battery at the proper temperature, a blower is activated when temperatures surpass the optimal range. Hence, the most important component in this process is a central temperature controller, which collects data from the sensor and coordinates the cooling system's response to maintain the battery within the specified temperature range. Furthermore, the air is considered to flow at a constant speed of 5 m/s, and the heat transfer coefficient is set at 20 W/m²K, aligning with standard values employed by previous researchers in the context of air-cooling systems.

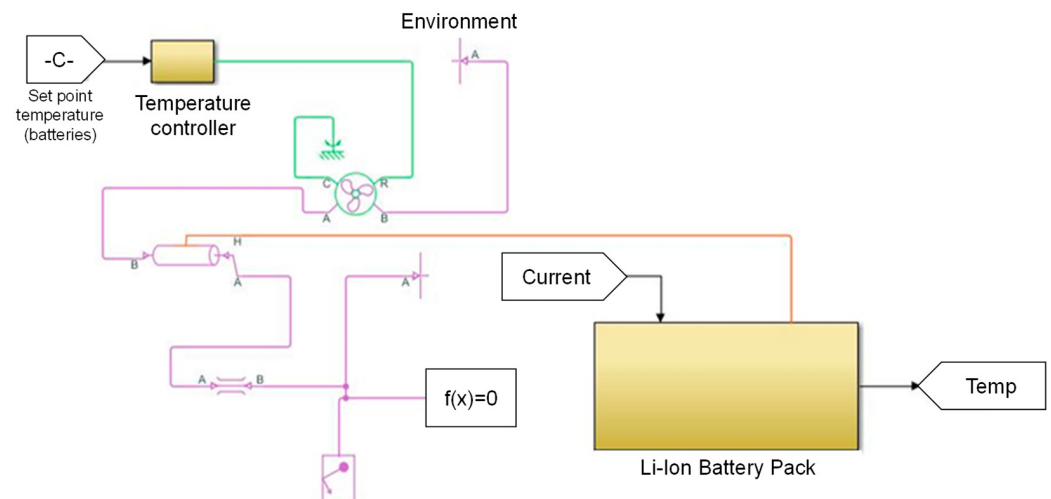


Figure 14. Simulation of the BTMS using an air cooling system.

The third simulation (Figure 15) involves the implementation of a battery thermal management system based on a liquid cooling system, with the focal component being the heat exchanger device. In this model, a pump is employed to facilitate the circulation of an ethylene glycol–water mixture through a network of pipes surrounding the battery pack. As the battery operates, it generates heat, which is then absorbed by the circulating coolant.

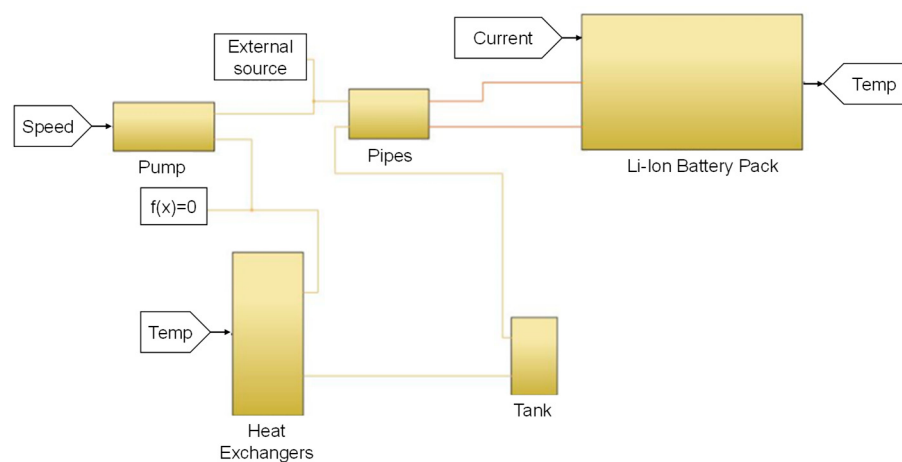


Figure 15. Simulation of the BTMS using an indirect liquid cooling system.

Subsequently, the heated coolant proceeds through the heat exchanger, where it dissipates the absorbed heat into the surrounding environment. To enhance the efficiency of the system, a dedicated tank is incorporated for the storage and management of the coolant. Furthermore, it is noteworthy that the heat transfer coefficient is set to $1000 \text{ W/m}^2\text{K}$, while the flow rate is established at 0.1 L/min .

The last model (see Figure 16) involves the simulation of a battery thermal management system using the immersion cooling method. In this system, the batteries are fully submerged in a dielectric liquid coolant within a specially designed enclosure. This enclosure is essential to the effective functioning of the cooling process. It is constructed with components and configurations that enhance heat transfer and maintain the batteries' monitored environment. Mineral oil is selected as the dielectric fluid for this simulation due to its non-conductive properties and excellent thermal stability, which enable efficient heat dissipation from the batteries. As the batteries operate and produce heat, the surrounding coolant rapidly absorbs this thermal energy, ensuring consistent and efficient cooling. In order to ensure exact regulation of the coolant temperature, a specialized liquid circulation system is utilized in tandem with temperature control units and monitoring systems.

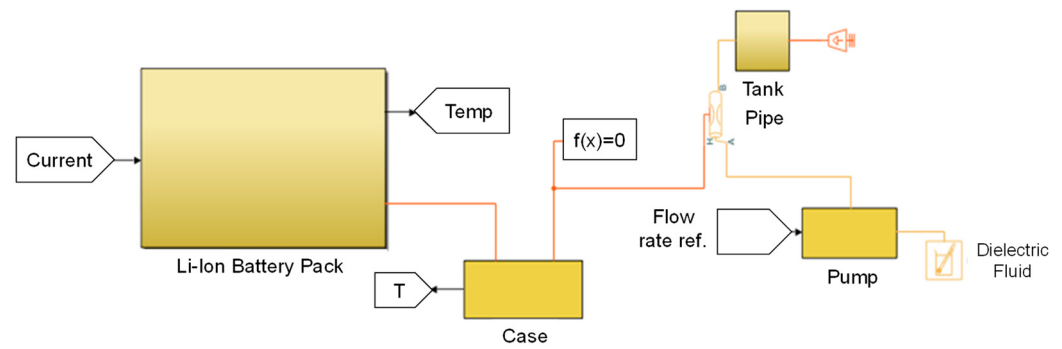


Figure 16. Simulation of the BTMS using an immersion cooling system.

On the other hand, Table 3 provides an overview of the properties of the coolants utilized in the simulations for each battery thermal management approach.

Table 3. Heat transfer medium for different BTM technologies.

Heat Transfer Medium	Air	Water/Glycol	Mineral Oil
Density (kg/m ³)	1.225	1069	2492
Specific Heat (J/kg K)	1006.43	3323	1833.8
Thermal conductivity (W/m K)	0.0242	0.3892	0.1281
Kinematic viscosity (m ² /s)	1.46×10^{-5}	2.582×10^{-6}	9.54×10^{-6}

5.2. Assumptions

In this study, several assumptions are made to simplify the modelling and simulation process. First, the influence of buoyancy during the coolant flow is neglected, as it is considered to have a minimal effect on the system's overall heat transfer behaviour. The dominant heat transfer modes within the system are convection and conduction, while the effect of thermal radiation is disregarded due to its negligible contribution at the operational temperature range of the system. Additionally, heat generation in the lithium-ion batteries (LIBs) is assumed to be solely due to irreversible Ohmic losses, with the heat generated from reversible entropy changes being ignored. Finally, the acceleration due to gravity is assumed to be constant at 9.81 m/s².

5.3. Governing Equation

In a battery system, heat is produced as a result of internal resistance when current passes through the cell. This phenomenon can be described by Joule's law [56], as shown in Equation (1), which states

$$Q_{gen} = I^2 R_{int} \quad (1)$$

In battery thermal management, the internal heat generated is crucial in influencing the temperature increase in the battery, particularly during high current usage. It is essential to effectively disperse this heat to maintain safe and optimal functioning.

Based on the first law of thermodynamics, each cooling system (air cooling, indirect liquid cooling, or immersion cooling) can be described by an energy conservation equation, which accounts for the heat transfer between the battery cells and their surroundings [56], as shown in Equation (2).

$$\frac{dT_{cell}}{dt} = \frac{Q_{gen} - Q_{loss}}{m c_p} \quad (2)$$

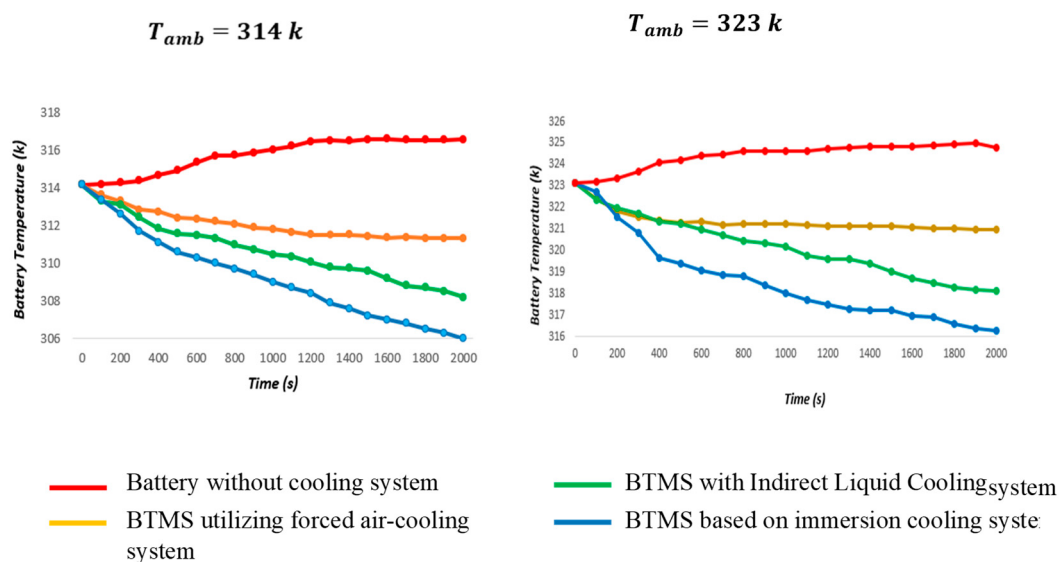
Equation (2) describes the rate of change in the battery cell's temperature over time for each cooling method, where $Q_{heat\ loss}$ is the convective heat transfer rate, which is dependent on the specific cooling method. Table 4 describe mathematically the thermal behaviour of each cooling system [56].

Table 4. Energy conservation equation of different cooling systems.

Cooling Systems	Thermal Behaviour Equation	Cooling Method
Air cooling	$\frac{dT_{cell}}{dt} = \frac{Q_{gen} - Q_{conv,air}}{m c_p}$ (3)	Heat from the battery cells is dissipated through convection with air blown over the surface by a fan.
	where: $Q_{conv,air} = hA(T_{cell} - T_{air})$ (4)	
Indirect liquid cooling	$\frac{dT_{cell}}{dt} = \frac{Q_{gen} - Q_{cond} - Q_{conv,coolant}}{m c_p}$ (5)	Coolant flows through a cooling pipe that is in contact with the battery. Heat moves from the battery to the pipe via conduction and then transfers to the coolant through convection.
	$Q_{conv,coolant} = h_{coolant}A(T_{pipe} - T_{coolant})$ (6)	
	where: Q_{cond} Conduction heat transfer	
Immersion cooling	$\frac{dT_{cell}}{dt} = \frac{Q_{gen} - Q_{conv,imm}}{m c_p}$ (7)	The battery is submerged in dielectric fluid, which cools it through convection as the fluid circulates.
	where: $Q_{conv,imm} = hA(T_{cell} - T_{dielectric\ fluid})$ (8)	

5.4. Results and Discussion

Figure 17 presents a comparative graph designed to analyse the temperature fluctuations in a Li-ion battery over time. This analysis is conducted under different ambient temperature conditions (314 K and 323 K) and with various cooling strategies in place. Numerical simulations are carried out for the comparison of the four systems in order to study their dynamic thermal response. The first simulation is a Li-ion battery pack without any cooling system (simulation described in Figure 13), the second simulation involves the Li-ion battery equipped with a forced air cooling system-based BTMS, as shown in Figure 14, the third simulation represents a Li-ion battery with a BTMS that relies on a liquid cooling system, as depicted in Figure 15, and the last configuration involves a Li-ion battery with a BTMS utilizing immersion cooling, as illustrated in Figure 16. Therefore, the objective of this study is to determine the most suitable strategy to maintaining the battery with the optimal temperature.

**Figure 17.** A comparative analysis of Li-ion battery temperature across time versus different cooling strategies.

The Li-ion battery without a cooling system simulation confirms that during battery operation and at various ambient temperatures, the lack of a cooling system resulted in a rapid increase in temperature, which can have a negative impact on battery performance and overall longevity. As explained previously, Li-ion cells generate heat due to the

chemical reactions that occur during the movement of ions and as a result of internal resistance, which underscores the necessity for a cattery thermal control system.

The outcome of the simulation for the Li-ion battery equipped with a thermal management system utilizing forced air cooling revealed poor efficiency in the cooling process. The ineffective cooling operation is due to both the limited heat transfer capacity of air as a medium for thermal conductivity and the additional energy consumption required for the auxiliary blowers. The BTMS based on the air cooling method is an uncomplicated and cost-effective system. However, it is inefficient in removing heat from the battery pack.

The last system is a liquid-based BTMS that can be categorized into indirect and direct cooling technologies, depending on the manner in which the cooling fluid interfaces with the battery cells. Regarding the indirect liquid cooling system, in which the transfer fluid ethylene glycol circulates through the pipes and the heat exchangers, the simulation illustrates that the liquid cooling system effectively removes heat from the battery. This leads to higher cooling efficiency compared to the air-cooling approach. Moreover, the advantageous thermodynamic features of the cooling fluid in heat exchange result in a high cooling efficiency for the liquid-based BTMS. Despite the effectiveness of this technology, the system implementation remains complex and costly.

Conversely, the direct liquid cooling system (BTMS based on immersion cooling) eliminates heat generated by the battery cells by directly submersing the battery within a dielectric liquid, which serves as the heat transfer medium. The simulation results demonstrate a remarkable performance compared to other BTM strategies. This technique allowed for the effective and speedy removal of heat from the battery, resulting in better thermal management. Therefore, immersion cooling efficiently dissipates heat because the coolant has a greater thermal capacity compared to air or other cooling fluids. Furthermore, immersion cooling minimizes system complexity by simplifying the system design. Despite these advantages, the high battery sealing requirements, the hidden danger of short circuits, and the high cost of cooling fluids limit their practical execution.

6. Conclusions

This research paper thoroughly examines various energy sources for electric vehicles, including lithium-ion batteries, which have proven to be the most efficient and widely utilized option. Alongside this, this study addresses the critical challenge of optimizing battery thermal management in electric vehicles (EVs), which is crucial for maintaining performance and longevity under varying thermal conditions.

Through simulations of a series-connected 12-cell lithium-ion battery pack, we compared three thermal management methods: air cooling, indirect liquid cooling, and immersion cooling. The results demonstrated that immersion cooling significantly outperforms the other methods, offering the most uniform temperature distribution and the highest heat transfer coefficient. Specifically, immersion cooling reduced temperature variation across the cells by 2.5%, compared to 1.2% for indirect liquid cooling and 0.6% for air cooling, ensuring superior thermal regulation essential for preventing thermal runaway and extending battery lifespan.

In conclusion, immersion cooling is the most efficient thermal management solution for EV batteries, surpassing conventional methods like air and indirect liquid cooling. This study positions immersion cooling as a cutting-edge and promising technology, with relatively few studies addressing its potential.

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Abbreviations

EV	electric vehicle
BTMS	battery thermal management system
GHG	greenhouse gas
EPA	Environmental Protection Agency
LA	lead–acid
NI-MH	nickel–metal hydride
Li-ion	lithium-ion
PCM	phase change material
SOC	state of charge
Symbols	
q	heat generation rate (J)
I	current (A)
V	voltage (V)
V_{ocv}	open circuit voltage (V)
T	temperature (K)
R'	internal resistance (Ω)
Q	heat transferred (J)
A	battery’s capacity (Ah)
$T_{battery}$	battery temperature (K)
T_{amb}	ambient temperature (K)
h	heat transfer coefficient ($W/(m^2K)$)
Nu	Nusselt number
λ	fluid thermal conductivity ($W/(m \cdot K)$)
l	length (m)

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