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Comprehensive insights into electric vehicle classification and lithium-ion battery technologies: Applications, disposal, and thermal management

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A B S T R A C T

Electric vehicles (EVs) have emerged as a critical solution to reducing greenhouse gas (GHG) emissions in the transportation sector. However, the effectiveness and sustainability of EVs are closely tied to the performance and environmental impact of lithium ion batteries (LIBs). This study provides an in-depth exploration of LIB technologies, focusing on battery thermal management systems (BTMSs), recycling processes, and the environmental consequences of large-scale battery deployment. We compare different battery types, including lithium-ion, nickel-metal hydride, lead-acid, and metal-air batteries, presenting their advantages, limitations, and sustainability metrics in a comprehensive table. Furthermore, this work investigates a variety of cooling methods, air, liquid, phase change material (PCM), and thermoelectric systems, highlighting their effects on battery lifespan, efficiency, and safety. The analysis extends to the environmental impacts of LIB production and disposal, exploring recycling technologies like pyrometallurgical, hydrometallurgical, and direct recycling processes. By integrating intelligent cooling systems and addressing challenges in waste management, this research bridges a crucial gap in the literature, offering innovative solutions to enhance LIB efficiency, longevity, and sustainability in EV applications.

Elektrikli araç sınıflandırması ve lityum iyon pil teknolojilerine ilişkin kapsamlı bilgiler: Uygulamalar, bertaraf ve termal yönetim

M A K A L E   B İ L G İ S İ

Anahtar Kelimeler:
Elektrikli araç
Batarya termal yönetim sistemleri
Atık bertarafı
Yenilikçi soğutma yöntemleri
Atık yönetimi

Ö Z E T

Elektrikli araçlar (EV'ler), ulaşım sektöründeki sera gazı (GHG) emisyonlarını azaltmak için kritik bir çözüm olarak ortaya çıkmıştır. Ancak, EV'lerin etkinliği ve sürdürülebilirliği, lityum iyon pillerin (LIB'ler) performansı ve çevresel etkileriyle yakından bağlantılıdır. Bu çalışma, LIB teknolojilerini derinlemesine incelemekte olup, özellikle pil termal yönetim sistemlerine (BTMS'ler), geri dönüşüm süreçlerine ve büyük ölçekli pil kullanımının çevresel sonuçlarına odaklanmaktadır. Çalışmada lityum iyon, nikel-metal hidrit, kurşun-asit ve metal-hava pilleri gibi farklı pil türleri karşılaştırılarak, avantajları, sınırlamaları ve sürdürülebilirlik metrikleri kapsamlı bir tabloda sunulmaktadır. Ayrıca, hava, sıvı, faz değiştiren malzeme (PCM) ve termoelektrik sistemler gibi çeşitli soğutma yöntemleri incelenerek, bunların pil ömrü, verimliliği ve güvenliği üzerindeki etkileri vurgulanmaktadır. Analiz, LIB üretimi ve bertarafının çevresel etkilerine kadar genişletilmekte ve pirometalurjik, hidrometalurjik ve doğrudan geri dönüşüm süreçleri gibi geri dönüşüm teknolojileri araştırılmaktadır. Akıllı soğutma sistemlerinin entegrasyonu ve atık yönetimindeki zorlukların ele alınmasıyla bu araştırma, literatürdeki kritik bir boşluğu doldurmakta; EV uygulamalarında LIB verimliliğini, ömrünü ve sürdürülebilirliğini artırmaya yönelik yenilikçi çözümler sunmaktadır.

NOMENCLATURE

EV	Electric vehicle	DC	Direct current
BEVs	Battery electric vehicles	PHEVs	Plug-in hybrid electric vehicles
ICEs	Internal combustion engines	FCEVs	Fuel cell electric vehicles
HEVs	Hybrid electric vehicles	FC	Fuel cell
EM	Electric motor	LIBs	Lithium ion batteries
BP	Battery pack	NiMH	Nickel metal hydride
AC	Alternating current	BMS	Battery management system
EOL	End-of-life	AGVs	Automated guided vehicles
HESS	Home energy storage systems	BTMS	Battery thermal management system
PCM	Phase change material	VCC	Vapour compression cycle
HTF	Heat transfer fluid	TCS	Thermoelectric cooling system
HVAC	Heating, ventilation, and air conditioning	TED	Thermoelectric device
HP	Heat pipe	LABs	Lead acid batteries
GHG	Greenhouse gas	GWP	Global warming potential

INTRODUCTION

The rising need to reduce the environmental impact of the transportation industry has pushed car producers to swiftly advance and broaden EV technologies. In 2021, worldwide EV sales hit 6.6 million, meaning a threefold increment in accordance with the year of 2019 (Paoli and Gül, 2022). Nevertheless, despite the increasing demand, several factors impede the broad acceptance of EVs. Major concerns involve the reliability of EVs for extended journeys and the durability of their battery packs (BPs) (Krishna, 2021). The efficiency of an EV BP is significantly affected by thermal conditions. Conventional LIB packs function optimally within a temperature range of 15°C to 35°C; outside this range, performance deteriorates, particularly below 15°C, where increased internal resistance leads to declined capacity (Hwang et al., 2024). On the other hand, temperatures above 35°C pose the risk of initiating irreversible reactions, bringing about thermal runaway and accelerating capacity loss (Ianniciello et al., 2018; Panchal et al., 2023). Considering the crucial role of thermal management in extending battery life, innovations in effective cooling systems are vital. Various thermal management approaches, including air cooling, liquid cooling, PCM based cooling, and thermoelectric cooling, present distinct benefits and drawbacks (Shahjalal et al., 2021). Air cooling is budget-friendly but less effective under high thermal conditions. Liquid cooling systems offer superior heat management, although they are more expensive. PCM-based systems use phase changes to capture heat but need improvements in thermal conductivity. Thermoelectric systems deliver exact temperature control but are pricier to install (Akbarzadeh et al., 2021; Weng et al., 2020). Environmental sustainability, especially in transportation, plays a crucial role in alleviating the impacts of climate change. As a major source of CO2 emissions, the road transport sector, with almost 1 billion vehicles worldwide, continues to depend significantly on fossil fuels (Shahzad and Cheema, 2024). In 2021, 90% of road transportation have been still fuelled by fossil fuels, with electrified vehicles accounting for just 12% of the global fleet (Rauf et al., 2024). The shift towards EVs is anticipated to lower emissions, as evidenced by the growing number of EVs on the road, which increased from 12 million in 2021 to 26 million in 2022. Forecasts indicate that by 2030, more than half of all passenger vehicles in the United States will be electric (BloombergNEF, 2023). Whilst the transition to EVs is crucial for meeting sustainability targets such as SDG 13 (Climate Action) and achieving Net Zero Emissions by 2050, there are still significant challenges. The manufacturing of LIBs, which are vital for EVs, involves energy-intensive procedures that produce GHG emissions due to the extraction and processing of materials like lithium, cobalt, and nickel (Xiong et al., 2020; Franzò and Nasca, 2021). Although fuel cell (FC) technologies offer an alternative, their hydrogen production can still lead to GHG emissions unless green hydrogen derived from renewable sources is utilised (Muthukumar et al., 2021). Efforts should be directed towards improving the efficiency of batteries and FCs through intelligent technologies, while simultaneously minimising the environmental effects of their production (Abdelkareem et al., 2021). What's more, policy backing, technological advancements, and infrastructure upgrades will be crucial for attaining Net Zero Emissions in the transportation sector.

This study aims to increase the efficiency of LIB used in EVs, improve their sustainability, and solve the challenges encountered in the thermal management of these batteries. While many studies in the literature address battery cooling methods or environmental impacts from a single perspective, this research comprehensively compares different battery types and cooling systems and examines recycling processes and battery waste management in detail. The innovative aspect of the study is that it provides a comprehensive analysis in terms of both technological and environmental sustainability by addressing these issues with an integrated approach.

In the following sections of the study, a general overview of EV classifications will first be provided (Section 2). Then, a more in-depth exploration of BEVs will be presented, offering much more detailed insights (Section 3). In the next section, comprehensive information on LIBs will be given, supported by comparative tables, and in addition to this, disposal methods will be examined from a broad perspective, discussing the environmental impact of waste management and recycling processes (Section 4). Following this, a classification of EVs using LIBs will be provided (Section 5). Subsequently, the effectiveness of thermal management systems and innovative cooling methods will be described in detail (Section 6). Finally, the key findings from this extensive review will be summarised in the Conclusion section, and general recommendations for future research will be offered (Section 7).

CLASSIFICATION OF ELECTRIC VEHICLES

Examining the extensive history of EVs, which remain popular today, reveals that their origins stretch back nearly 200 years. EVs first flourished in the 1830s (Chan, 2007) and gained significant traction over the next five decades, leading manufacturers to pivot their production efforts toward these vehicles. Consequently, many companies continue their production, with EVs even dominating the taxi fleets of London (Mourato et al., 2004). However, the era's limited technological advancements pose challenges such as battery issues, fuel costs, and range limitations. As companies struggled to overcome these obstacles, Wicks (2003) introduced a groundbreaking solution with the internal combustion engine (ICE) in 1896. This innovation significantly improves vehicle efficiency and convenience, dramatically declining EV usage as consumers favour the new technology. Despite the initial success, the widespread adoption of ICEs contributes to environmental issues, including global warming, which has become increasingly apparent in the 21st century. To combat these challenges, authorities implement incentives to encourage the resurgence of EVs as a cleaner alternative. Today, EVs are at the forefront of the decarbonisation movement due to their lack of exhaust emissions and reliance on battery-powered electrical energy. The variety of modern EVs can be categorised, as illustrated in Fig. 1.

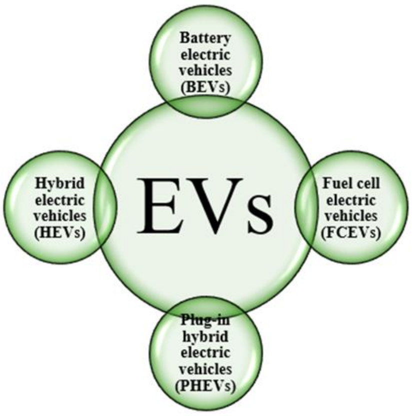

Fig. 1. Categories of EVs.

Battery Electric Vehicles

Battery EVs (BEVs) provide the ability to move from one point to another thanks to the batteries they contain that can be recharged and used repeatedly (Aggarwal and Singh, 2025). This battery system is designed to cover the majority of the vehicle's subsystem and provides power transmission through flexible electrical cables (Delucchi and Lipman, 2001; Maggetto and Van Mierlo, 2000). Therefore, it plays an active role in the market by delivering power only through electrical transmission, completely free of ICEs and its components and fuel tank area. These battery cells are exceptionally environmentally friendly, considering the harmful gases emitted from ICEs (Peng et al., 2012; Amjad et al., 2010; Tie and Tan, 2013). For this reason, it may be a salve for the problem of not experiencing full seasons due to the global warming problem, the effect of which is felt even more today (Mandev et al., 2021; Plötz et al., 2017). In addition, the energy transfer efficiency of BEVs is higher than those in the ICE categories, and the fact that the electricity it receives power can be met by renewable energy sources makes it much more attractive. Additionally, the high efficiency of BEVs, their very good acceleration ability, their relatively affordable charging and the ease of charging with a single plug when not in use make them extremely impressive (Castro et al., 2017; Shareef et al., 2016). Also, BEVs are extremely suitable for the use of such conditions, as the stop-start phenomenon is high in places where speed is restricted, and vehicle density is high (Raslavičius et al., 2015). Fig. 2 shows a demonstration with arrows indicating how a BEV system works integrated with its powertrain.

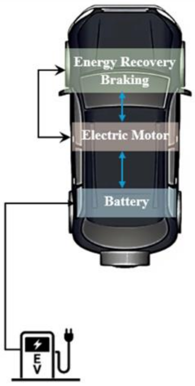

Fig. 2. Descriptive representation of BEV system and powertrain with arrows.

On the other hand, the charging process of BEVs is extremely long compared to ICEs, which means that it has some struggles. So much so that, considering the use of a charger below its capacity, the process of charging the vehicle can take almost a quarter of a day or sometimes half a day. At best, included charging time takes 15 to 45 min. As can be seen from here, it is a problem that still needs to be developed in terms of filling compared to ICEs (Lyu et al., 2019). In addition, problems may arise due to the limited range for long-distance driving, and drivers are still concerned about the lack of station installation in countries (Kumar and Revankar, 2017). For this reason, improvement efforts for its performance continue. Among the problems reported in the studies and as feedback of user problems, the problems experienced are generally the heating problems of the battery and the battery capacity, which focuses the studies here. It is known that changes in the temperature of the battery while it is running or accelerating will cause its effectiveness to decrease after a while and, therefore, directly affect its life and performance (Verma et al., 2021). Additionally, the parameter that determines the range varies depending on the capacity of the battery but modifies between approximately 100-400 km. The charging time of the battery depends on the battery capacity and also on the charging scheme and serial/parallel connection type. Whilst studies to increase travel distance continue, researchers suggest that hybrid EVs (HEVs) can be used as a solution to this problem (Ehsani et al., 2021; Chen et al., 2021; Lan et al., 2021).

Hybrid Electric Vehicles

HEVs exhibit behaviours characteristic of both EVs and ICE vehicles (Carlucci et al., 2018). The electric motor (EM) is utilised when petrol or diesel is depleted, during low-speed scenarios, and while starting the vehicle. Conversely, the ICE is favoured for achieving higher speeds and delivering additional power. Therefore, an HEV has the capability to generate energy from at least two sources (Wu et al., 2012). Additionally, while the ICE version is more frequently used, the EM is employed as needed (Zhao et al., 2008). Unlike BEVs, where the EM is recharged by plugging into an electrical outlet, the HEV's EM is recharged through the energy generated from vehicle movement while running on petrol, excess power, and braking. Thus, in terms of the distance covered, HEVs can compete with ICE vehicles and surpass BEVs. This is due to their ability to run on both an ICE and electric power (Saju et al., 2022). Fig. 3 illustrates the components of a typical HEV and the integration of each part through arrows.

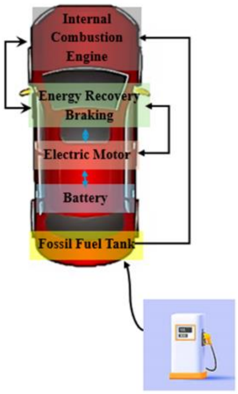

Fig. 3. Descriptive representation of HEV system and powertrain with arrows.

When enumerating the advantages of HEVs, they provide greater fuel economy due to their ability to recharge from kinetic energy and braking (de Moura Oliveira et al., 2016). Unlike BEVs and other vehicles requiring charging stations, HEVs do not necessitate a charging station, offering an active solution to the range problem. They emit fewer pollutants compared to ICE vehicles, and the EM enhances performance by providing torque during acceleration (Bagheri et al., 2021). However, the advanced technology and additional components result in a higher purchase price than ICE vehicles, and the complex system may lead to higher maintenance costs (Denton, 2020). The BP may also fail over time, leading to increased expenses if continued usage is pursued. The limited use of the electric mode often results in a predominant reliance on the ICE mode, which still contributes to some level of pollutant emissions (Balali and Stegen, 2021). The existence of two or more energy systems in HEVs necessitates examining them under different configurations, namely series, parallel, and series-parallel (dual) HEVs.

Series hybrid electric vehicles

In this configured system, the ICE has no role in creating the motion phenomenon. On the contrary, the function of this engine is used only to store the battery by giving power to the generator. Therefore, in this system, the main source of movement of the vehicle is EMs. It can be provided through a rectifier that converts alternating current (AC) to direct current (DC) to realise storage in the battery (García and Monsalve-Serrano, 2019). Considering its efficiency, this configuration is known to perform less than others (Onwuchekwa and Kwasinski, 2011). The reason for this lies in the fact that the parts required in these vehicle groups depend on the ICE, generator and EM. When we look at the energy structures of such parts, the constant conversion of mechanical energy to electrical energy and then back to mechanical energy makes this configured system inefficient (Sivertsson and Eriksson, 2017). Since serial HEVs derive their main source from the electric engine and do this thanks to ICE, these systems must have a large structure to realise this phenomenon, and therefore, their cost is high (Chau and Wong, 2002). Thus, vehicles in this configuration group demonstrate their suitability in the production of heavy tonnage vehicles (Ehsani et al., 2007). In a nutshell, series HEVs use an EM to get from point to point. This EM moves thanks to ICE. ICE continues its duty until the battery is fully charged. When the battery is fully charged, the ICE is disabled, and it travels distance continuously with the EM. Since the main source is the EM, these systems can be called a solution to the problem of burning fossil fuels.

Parallel hybrid electric vehicles

It utilises ICE and EM power to create the motion effect of parallel HEVs. These can exhibit thrust in three different settings. These may be capable of being driven solely by an ICE, solely by an EM, or both. When both are used, it receives power from both motors and transmits it as the sum of torques, and by using this power to rotate the wheel, movement energy is obtained. In these vehicles, the primary energy capability is provided by the ICE, while the electric engine undertakes the secondary duty (Lanzarotto et al., 2018). Having a primary and secondary power source, these vehicles play a supporting role in fuel consumption due to their ability to compensate for the consumption of fuels in order to travel distance (Zhao et al., 2020). One of the advantages of this configuration compared to serial HEVs is that the EM is in the background, that is, backup energy, and thus, it is easy to minimise the size of the battery. In addition, the ability to use both power sources means that it can exhibit faster going performance, for example, when reaching high speeds, the ICE is activated to a certain extent, and then the EM is activated and transfers the power as the sum of the two. In addition, another advantage of these systems using the powertrain is that they have a reduction effect of approximately 70% on fuel economy, an approximately 40% improvement in waste gas emissions, and less transmission losses with an approximately 6% increase in engine efficiency (Olabi et al., 2022). On the other hand, there are some challenges to the use of parallel HEVs. For example, the need for two power supplies to work in perfect harmony indicates a more complex structure, which may result in high costs in case of a possible service. In order for the accents to work in harmony with each other, extremely sensitive mechanisms are used, which may increase the purchasing cost. Additionally, its use of a limited EM may cause emissions, although its environmental impact is improved.

Series-parallel hybrid electric vehicles

Another name given to these vehicle types is double HEV (Gupta et al., 2009). It generally refers to a configuration that combines multiple power supply types to increase vehicle performance, efficiency and flexibility (Meydani et al., 2024). These power supplies are typically marketed as a dual hybrid system. The main goal here is to integrate dual energy storage and propulsion technology to achieve power distribution, fuel efficiency and emission reduction. Additionally, as the name suggests, this configuration embodies the advantages of both series and parallel HEVs. The fact that they include these two features makes these systems advantageous. Namely, although there is a reduction in engine volumes compared to series and parallel type HEVs, it has been proven that the system performs its duty more efficiently in lower and higher acceleration curves (Tran et al., 2020). The efficiency of this system comes from estimating speed and power and determining which situation will be more cost-effective and performant. With the presence of the EM in the system, the emission rate decreases. It offers a more flexible working option with its own predictive ability regarding power management. On the other hand, the fact that the system has multiple power supplies, integrated operation, etc., is a sign of its high cost. In summary, dual-HEVs represent a promising approach to achieving greater fuel efficiency and reducing environmental impact by synergistically using multiple power sources. As technology advances, it may be inevitable that these systems will become more complex, offering improved performance and efficiency.

Plug-in Hybrid Electric Vehicles

Plug-in HEVs (PHEVs) are expected to play an important role in ensuring significant reductions in GHG emissions in the field of transportation until they can be charged frequently to contribute to electric operation (Poullikkas, 2015). The rechargeability results in the integration of an even larger battery to make PHEVs more affordable than other HEVs, a significant innovation in optimising fuel costs (Hu et al., 2016; Chen et al., 2022a). In addition to being a serious innovation in optimisation, there is information in the literature that the fact that it comes to the market with a large battery improves the distance range to some extent (Xie et al., 2018). It is emphasised in the literature that the best solution to low/zero CO2 emissions by 2030, which governments target, is PHEVs, not BEVs, and that the trend towards this should increase (Boretti, 2022). The low specific energy density of batteries fully integrated into BEVs indicates that these vehicle types should have greater battery potential (Denton, 2020). However, since the weight of the vehicle will directly increase in such an optimisation attempt, there will be a similar decrease in performance. For this reason, the adoption of smaller batteries by PHEVs can again be explained as a positive feature of PHEVs. Therefore, the fact that PHEVs are a combination of ICE and battery (Sanguesa et al., 2021) but work in very good harmony reveals that it is necessary to focus on this type of vehicle (Boretti, 2021). In addition, it has features that reduce potentially harmful waste gases caused by traditional vehicle types, thanks to the combination of both technologies (Kazemzadeh et al., 2022). This diminishing effect is due to the mitigation of the use of oil, its contribution to fuel economy and its full support to much lower waste gas emissions (Poullikkas, 2015). On the other hand, in PHEVs, where serious efforts are spent to work in perfect harmony with each other, in case of possible improper management, problems such as overloads, voltage fluctuations, and energy inefficiency may occur in the system (Moeini-Aghtaie et al., 2022). Additionally, another disadvantage is that although this configuration has a certain ability to drive on electricity (60 km for Mitsubishi 2024 Outlander) (Mitsubishi, 2024) when looking at fuel consumption data, researchers point out that it is higher than other vehicle types (Plötz et al., 2020).

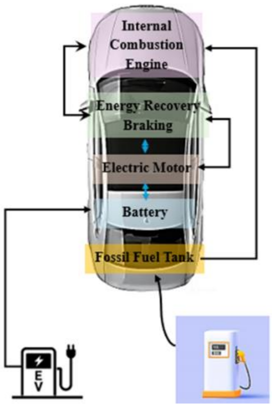

Fig. 4. Descriptive representation of PHEVs and powertrain with arrows.

Fuel Cell Electric Vehicles

There are competing vehicle types that keep taking determined steps to reduce harmful gas emissions caused by ICE vehicles (Joshi et al., 2022). These are BEVs and FCEVs. The common feature of these vehicles is that they have zero harmful waste when considering harmful emissions. Having zero waste means that it is innovative and clean energy, which is called green energy on the low/zero carbon technology scale (Hawkins et al., 2013). FCEVs use FCs to produce electricity, and this FC is among the advanced EV models that have a structure that produces electricity by the reaction of hydrogen and oxygen (Boretti, 2024). Therefore, it can be summarised as a device that produces electrical energy as a result of a chemical reaction. The most basic physical structure of an FC consists of an electrolyte layer in contact with the anode and cathode on both sides (Pramuanjaroenkij and Kakaç, 2023). The table below presents the advantage of electrolyte type, operating temperature and operating temperature range of common FCs.

Table 1. Includes which types of electrolyte FC, their operating temperatures and their advantages (Tariq et al., 2024; Gao et al., 2023).

Electrolyte FC type	*Approximate working temperature range (°C)*	*Prof of having that range*
Proton Exchange Membrane	40 – 80	Low operating temperature allows for quick start-up times and makes them suitable for applications in vehicles and portable power sources.
Direct Methanol	50 – 120	Simplified fuel logistics and lower temperatures than solid oxide as well as molten carbonate types but lower efficiency and power density than hydrogen-fed proton exchange membrane.
Alkaline	65 – 260	High efficiency and exemplary performance in space applications, but sensitive to CO2 contamination, which can reduce lifespan.
Phosphoric Acid	150 – 200	Higher operating temperature improves tolerance to impurities in the fuel, but longer start-up times compared to Proton exchange membrane ones.
Molten Carbonate	550 - 650	High operating temperature allows for internal reforming of fuels and high efficiency but requires materials that can withstand high temperatures.
Solid Oxide	600 – 1000	High operating temperature allows for internal reforming of hydrocarbons and high efficiency but results in longer start-up times and requires high-temperature materials.

Proton exchange membrane FC has the most important place among the electrolyte types mentioned above. The most important reason for this, as stated in the literature, is that it saves time when refuelling, travels further, and pioneers zero carbon emissions (Jian and Wang, 2022). Moreover, this FC has a number of features such as low operating temperature, high increase in power density, very efficient performance as a result of the reaction and improved response time (Fan et al., 2021). It is stated that the performance efficiency is numerically between 50 - 60% in the literature (Yue et al., 2021). Additionally, it has a lifespan of over 5000 hours in vehicle use (Jian and Wang, 2022). Therefore, although FCs are the most popular, it is clear that there is still a need for research on extending their life (Zheng et al., 2013).

Li and Taghizadeh-Hesary (2022) state that the energy density of FCEVs is the same as that of a gasoline vehicle. However, they have reported that although they have a similar scale, FCEVs have much better fuel economy. For example, they say that a vehicle with 5 kg of hydrogen in its tank can travel 500 km. Other advantages published for these vehicle types are that tank filling is as fast as the filling speed of gasoline or diesel vehicles. For this reason, it is appropriate to use this type of system in heavy tonnage vehicles such as intercity buses that need to travel long distances or trucks that serve as transportation. The suitability here is due to both the problem-free driving experience over long distances and the provision of clean energy. Because the output of FCEVs emits water vapour instead of harmful gas. Another advantage is that it is better than BEVs in cold winter conditions due to its operating performance at low temperatures. On the other hand, there is a barrier to the FCEVs. Another reason is that its lifespan is very limited. Many researchers have evaluated the lifespan of FCEVs (Gao et al., 2023; Min et al., 2022; Fu et al., 2020; Hou et al., 2023). According to Jouin et al. (2016), for the FCs discussed in their paper, specifically Proton exchange membrane FC, the current operational lifespans are about 2000-3000 h, whereas 8000 h are required for transportation applications and 100,000 h for stationary purposes. The common denominator is that researchers aim to intensify their research to extend this period.

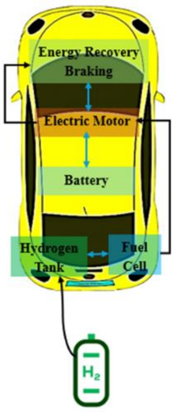

Fig. 5. Descriptive representation of FCEVs and powertrain with arrows.

A BRIEF EXPLANATION OF BEVs

BEVs are a critical component of the modern push towards sustainable transportation. Defined as vehicles that are powered entirely by electric energy stored in rechargeable batteries, BEVs do not rely on ICEs or fossil fuels. This absence of emissions at the point of use makes them a cornerstone of efforts to reduce GHGs and urban air pollution.

At the heart of a BEV is its BP, which stores electrical energy to power the vehicle. Typically, these packs consist of numerous individual cells arranged in modules to meet the desired voltage and capacity. The EM then converts this electrical energy into mechanical energy to drive the wheels. BEVs commonly use either asynchronous (induction) motors or synchronous (permanent magnet) motors. The power electronics controller manages the flow of electrical energy between the battery and the EM, ensuring the motor receives the correct amount of power to match the driver's inputs and the vehicle's operating conditions. A thermal management system is essential to maintain optimal operating temperatures for the battery, motor, and power electronics. This system ensures the efficiency, performance, and longevity of the components. The onboard charger converts AC from the charging station to DC, which is suitable for the BP. The charging process is managed to protect the battery and maximise its lifespan. Additionally, the regenerative braking system recaptures kinetic energy during braking, converting it back into electrical energy stored in the battery, enhancing overall efficiency and extending the vehicle's range.

BEVs operate on a straightforward yet sophisticated principle, relying entirely on electricity stored in a BP. At the bottom centre of a BEV is its BP, usually composed of LIB cells, known for their high energy density and longevity (Gao et al., 2022). These batteries store the electrical energy needed to power the vehicle. When the driver starts the car, the energy stored in the BP is directed to an inverter. This inverter plays a crucial role in converting the DC electricity from the batteries into the AC required by the EM. The EM, now powered by this AC electricity, converts the electrical energy into mechanical energy, which propels the vehicle forward. The power electronics controller manages this process, which ensures the efficient flow of electricity from the battery to the motor. It regulates the motor's speed and torque, providing a smooth and responsive driving experience. As the car accelerates and decelerates, the controller continuously adjusts the power flow to match the driver's input. One of the unique features of BEVs is their ability to recover energy during braking. When the driver applies the brakes, the EM reverses its function and acts as a generator (Singh, 2024). This process, known as regenerative braking, converts the vehicle's kinetic energy back into electrical energy, which is then fed back into the BP. This not only extends the driving range but also enhances the vehicle's overall efficiency. Charging a BEV is a straightforward process, involving plugging the vehicle into an external power source. This can be done through standard electrical outlets, dedicated home charging stations, or public fast-charging stations. The BP is replenished with electrical energy, readying the vehicle for the next journey. Throughout this process, thermal management systems work to maintain the optimal temperature of both the BP and the EM. These cooling systems ensure that all components operate efficiently and safely, extending the lifespan of the battery and preventing overheating. Unlike traditional vehicles, BEVs typically employ a single-speed transmission. This simplicity is due to the EM's ability to provide consistent torque across a wide range of speeds, eliminating the need for multi-speed gearboxes. In summary, BEVs operate by converting stored electrical energy into mechanical energy to drive the vehicle, with advanced control systems managing the process. Regenerative braking recaptures energy during deceleration, and efficient thermal management ensures the system runs smoothly. Charging replenishes the battery, making BEVs a clean and efficient alternative to conventional vehicles.

Fig. 6. Representation image of which contains inside of EVs (Tesla Model 3, 2024).

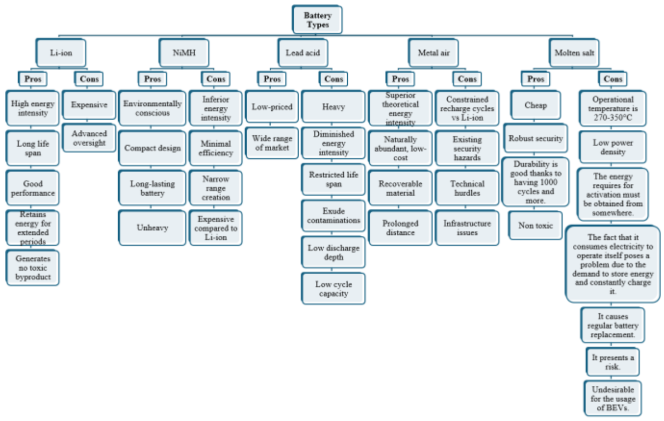

Fig. 7. Hierarchical table about the battery types' pros and cons.

Fig. 7 reveals a hierarchy table, and the best solution is sought by revealing the advantages and disadvantages of the battery types that can be preferred in BEVs. Accordingly, batteries are examined in 5 different types in this study. These are divided into Li-ion, nickel metal hydride (NiMH), lead acid, metal air and molten salt batteries.

LIBs offer numerous advantages over different types of batteries. As seen in Fig. 6, it is no coincidence that LIBs, which provide numerous advantages, are the subject of extensive research interest (Chavan et al., 2024; Saxon et al., 2024; Behi et al., 2022; Behi et al., 2021; Khosravi et al., 2024). One of the most significant advantages of LIBs is their high energy density. This attribute stems from the fact that they contain lithium, the lightest of the metal elements, which also has the highest electrochemical potential (Rangarajan et al. 2022). Therefore, this combination of high energy density and lightweight nature makes LIBs particularly popular. The energy density of batteries is measured in watt-hours per kilogram (Wh/kg). According to the literature, the energy density of LIBs ranges from 90 to 220 Wh/kg (Bhatt and Darieby, 2018). Another key advantage is their long lifespan and robust solid performance metrics (Loganathan et al., 2021). Additionally, LIBs have the ability to retain energy for extended periods and do not cause pollution, which are undeniably beneficial features. However, these batteries also have some drawbacks. For instance, their complex structures are necessary to ensure safety and longevity. Moreover, large LIBs pose safety risks related to overheating. Regarding production costs, although there is a significant decline from 2006 to 2020 (from $2000 to the $500 range), future projections suggest that costs will remain between $250 and $500 (Andwari et al., 2017). Despite this reduction, the cost of batteries still constitutes the most considerable expense in BEVs, indicating that it remains relatively high. As supplementary pros features, the loss in capacity at high loads is 0, and there is a fast-charging time (PowerTech Advanced Energy Storage Systems, 2020). Its efficiency is approximately in the range of 92-98%, and the depth of discharge is in the range of 80-95%, which is at very reasonable levels (Yanamandra et al., 2022). It has 4000-5000 cycles and can operate at 98% capacity at 40°C and 80% capacity at -20°C (PowerTech Advanced Energy Storage Systems, 2020). In terms of charging performance, high temperatures in LIBs may increase the charging speed but might cause problems in the life of the battery. Charging at low temperatures is dangerous due to the risk of freezing (Liu et al., 2019). Furthermore, the distance it can travel with a single battery is a serious distance of nearly 400 km.

The most notable positive features of NiMH batteries are their slim design and lightweight (Maeda et al., 2021). Despite their thin structure, these batteries have a relatively good lifespan performance. Additionally, they are considered safe (Edalati et al., 2022) due to their chemical structure. While NiMH batteries share a similar chemical composition with nickel-cadmium batteries, they are approximately 1.5 times better in terms of energy density (Blumbergs et al., 2021). However, there are significant disadvantages to NiMH batteries. One major drawback is their higher cost compared to LIBs (Arun et al., 2022). Despite this higher cost, the energy density of NiMH batteries is quite low, recorded at only 60-80 Wh/kg (Li et al., 2022). Consequently, these low-energy-density batteries are unsuitable for BEVs. The low energy density results in a reduced range and lower efficiency, making NiMH batteries impractical for BEVs, which already face range limitations. Furthermore, for high temperatures, for example, the maximum charging allowance for 60°C is 45%, while it is 70% for 45°C. Low temperatures have a 0.1 C charge rate for -17≤°C≤0, while it has a 0.3 C charge rate for 0≤°C≤6 (Muslimin et al., 2022). Additionally, whilst lead acid batteries (LABs) have a cycle capacity of 300-500 cycles and a slightly longer cycle life compared to some options, they generally have a shorter cycle life than others (Symeonidou et al., 2021). With a single battery, the distance it can travel is approximately between 75 and 150 miles (Chian et al., 2019).

LABs have several drawbacks, including low depth of discharge, limited life cycle, and reduced efficiency. LABs have a short lifespan which means that it has only useable for approximately 8.5 years (Yudhistira et al., 2022). Under high load, they experience a capacity loss of around 40%, leading to inefficiency and a quicker end-of-life (EOL). Additionally, these batteries are heavy and can waste about 15% of energy. Their performance is notably poor at both low and high temperatures, with significant degradation in cold conditions. However, despite these limitations, LABs are relatively inexpensive and boast a high recycling rate of 99% (Yanamandra et al., 2022). Since lead is highly toxic, careful handling is essential during its use, production, and disposal to prevent serious adverse effects on both human health and the environment. Lead's potential to contaminate can pose significant environmental hazards. Furthermore, with the resurgence of EVs in the 1900s, LABs, due to their numerous drawbacks and limited range, fell out of favour for automotive applications. Additionally, their charging performance varies with temperature: at high temperatures, the voltage threshold drops to 3 mV/°C, while at low temperatures, they can be charged at freezing points of 0.3°C or lower. Moreover, LABs, which are widely used in energy storage, owe this feature to their simple process and low production cost. The disadvantages stated in the literature can be listed as follows a) has low energy density, short life and low discharge depth (Fan et al., 2023). For example, after approximately 200-300 full discharge cycles, the capacity of a new battery can decrease significantly, dropping to around 80% (Krieger et al., 2013). This directly affects its performance. b) It contains low energy density of 30-50 Wh/kg (Das et al., 2021), high volume and mass, and high toxicity due to the element lead. It can travel only 22 miles on a single battery (Chian et al., 2019).

Metal air batteries are known as a type of battery that has a metallic element in its anode and air in its cathode and works in this way. It can be integrated with different metallic elements. For example, multiple metal air batteries can be created by using zinc, aluminium, lithium, iron and silicon elements and air as cathode (Liu et al., 2022b). They can typically offer medium specific power and much better specific energy density. So much so that these values can theoretically reach almost 2 to 10 times better than LIBs (Wang et al., 2018). The high energy density of lithium-air batteries is due to their use of ambient air directly at the cathode, which creates an oxidising effect during discharge. Lithium-air batteries are theoretically described as having the highest energy density, around 5928 Wh/kg, while iron-air batteries are noted as having the lowest energy density (Kalampoka, 2023). Additionally, lithium-air batteries are relatively affordable compared to other types. This cost-effectiveness stems from the fact that the air used at the cathode is naturally abundant and free of charge, and the metals utilised in the anode are also inexpensive, further contributing to the lower overall price. On the other hand, metal anodes face several challenges, such as corrosion, hydrogen production, formation of passive layers, dendritic growth, electrode deformation, and energy loss due to self-discharge. The air anode encounters obstacles like a lack of efficient catalysts for both oxygen reduction reaction and oxygen evolution reaction, electrolyte stability issues caused by impurities and dissolved gases, and gas diffusion blockages due to side reaction products. The selection of an electrolyte, a crucial component for efficient electrochemical reactions, presents technical barriers, including side reactions with the anode, reactions with CO_2 from the air, and low conductivity (Wang et al., 2019).

Molten salt batteries, also known in the literature as ZEBRA batteries, stand for "Zeolite Battery Research Africa" (Landmann, 2022). These batteries are notable for their cost-effectiveness and their safety profile (Wang et al., 2024a). Unlike LABs, molten salt batteries do not contain toxic materials, and they are distinguished by their impressive cycle life. However, despite these advantages, molten salt batteries also have significant drawbacks. One notable disadvantage is their relatively low efficiency, with energy efficiency ranging only between 75% and 85%. Additionally, molten salt batteries operate within a narrow temperature range, specifically between 270°C and 350°C, which is much higher than other battery types (Lee et al., 2023). This narrow operational temperature range is not only a limitation but also an indication of their specific power capacity, which is among the lowest in their class at just 100-120 Wh/kg (Andújar et al., 2022). Their energy density is also relatively modest, standing at 160 Wh/L. The requirement for such a high operating temperature is a significant drawback. Maintaining this temperature requires substantial energy input, which not only consumes energy but also contributes to a higher rate of wear and tear on the battery, potentially shortening its lifespan. In practical terms, for a battery to cover a distance of 100 km, studies indicate that a ZEBRA battery would need to weigh around 200 kg (Chian et al., 2019). This weight is considerably heavier compared to other battery types. In terms of range, molten salt batteries face a considerable limitation as well. The literature indicates that a single molten salt battery typically provides a range of only about 120 miles (Chian et al., 2019). This limited range is a significant issue when considering the practical applications of these batteries.

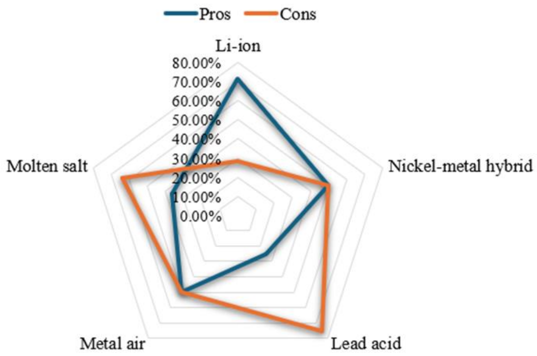

Fig. 8. Pros and cons of various battery types with radar perspective.

As it is seen that Fig. 7, its description paragraphs, and also Fig. 8 are helpful for us to understand which one is the best choice and why the literature is fully concentrated on that. Hence, it is selected among those who are really interested in this area is LIBs. So now, let's have a look much deeply for LIBs.

DEFINITION OF LITHIUM-ION BATTERIES

LIBs are a type of battery that can be used over and over again when recharged, and their use has become widespread with the rebirth of EVs. The reason for calling rebirth is that for M. Stanley Whittingham, he acted normally at unbelievable research which was called the first worked lithium battery by using titanium disulfide as the cathode and lithium metal as the anode in the 1970s (Manfo, 2023). However, since it could not be commercialised because of thinking safety problems. After 10 years, John B. Goodenough conducted to the improvement of that battery's design thanks to his discovery of cobalt oxide as a cathode material in the battery (Mizushima et al., 1980). Akira Yoshino (2022) could do the commercialised one by replacing the lithium metal anode with a carbon-based material (graphite) in the 1990s. Finally, their work was crowned by being awarded the Nobel Prize for their serious contributions in 2019 (O'Brien and Nicholson, 2024). It has a wide range of uses, from mobile phones to EVs. So much so that with the increasing interest in EVs, estimates predict that there will be more than 220 million EVs on the road worldwide (Rajaeifar et al., 2022). Additionally, LIB production will be forecasted to manufacture exceed 10 million tonnes annually for 1 year later (Ghafari et al., 2023). Hence, shortly, this means that LIBs will be on the road with this much improved version. LIBs derive these features from a number of features. It offers a high energy density, deliver superior performance, and is more cost-effective to acquire compared to other battery types (Jung et al., 2020; Abdul-Jabbar et al., 2021; Bibin et al., 2020). For instance, it is able to store energy density for nearly 180 Wh/kg at the cell level as well as for level of battery it is reached 120 Wh/kg. However, it is indicated previously that LIBs are still developing by the researcher actively, therefore, for 2020, it is exceeded the value of specific energy limit up to 200-250 Wh/kg whereas this value increased for 2030 is estimated 450 Wh/kg at least (Van Mierlo et al., 2021). That's why LIBs' market share is dominated up to almost 50%, and this is followed by lead acid with 43% (Demirocak et al., 2017). In addition to the development of both EVs and directly affected the rising up of LIBs, they have been expected to also increment of the market size for the future trend.

They consist of three portions which are called cathode, anode, and separator placed in lithium salt solution. In an LIB, the cathode, or positive electrode, plays a crucial role as it is the primary source of active Li-ions. Fig. 9 indicates the illustration of the LIB internally.

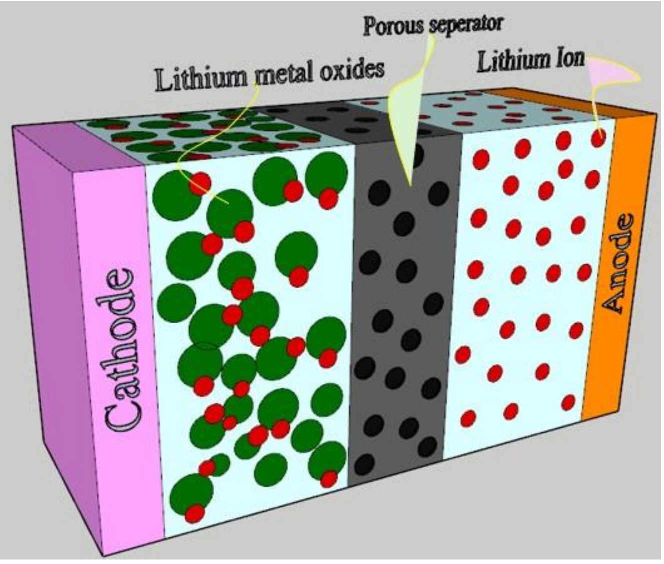

Fig. 9. Representative view of the LIB internally.

To achieve high energy capacity, the cathode material must be designed to accommodate a substantial amount of lithium during its formation. Additionally, it is essential for this material to facilitate the reversible exchange of Li-ions with minimal structural alterations, ensuring a long cycle life and high coulombic efficiency. The cathode also has to be insoluble in the electrolyte and should be synthesised using cost-effective reagents. Moreover, it is important for the material to exhibit high Li-ion diffusivity and good electronic conductivity to maximise energy efficiency. Typically, the cathode materials in commercially available LIBs are either lithiated metal oxides or phosphates. Well known recent cathode materials are LFP, LCO, NCA, and NMC (Ramar and Wang, 2020), also LMO and LTO. In Table 2, all these are briefly explained. On the other side, the anode face should be stored lithium with huge capability and stabilised during cycling. It is known for the most usage is graphite which is founded by Yazami (Yazami, 1999). The separator in a LIB is a porous membrane that permits the passage of Li-ions whilst acting as a barrier to prevent electrical short circuits by insulating the positive and negative electrodes.

Examining the structure of LIBs reveals that three configurations are typically favoured: prismatic, cylindrical, and pouch. In EV technology, cylindrical and prismatic LIBs are the most commonly utilised, with cylindrical cells being especially prominent in numerous EV designs. In Table 3, there is a fully comparison information in detail.

Disposal of Spent Lithium-Ion Batteries

The handling of spent LIBs involves various methods, including reuse, recycling, landfilling, and, regrettably, illegal disposal. The specific disposal methods employed locally are influenced by national legislation, recycling infrastructure, collection systems, consumer practices, and the battery commerce sector (Skeete et al., 2020).

Reuse

Batteries are typically recommended for retirement when their electric energy capacity falls below 80% of their original value (Li et al., 2024). Despite this decrease in capacity, a substantial amount of energy remains in these EOL LIBs, presenting significant opportunities for "reuse" options. This aspect is economically significant as power batteries can constitute up to approximately 50% of the total vehicle cost (Li et al., 2018). Even when evaluated with less favourable assumptions, repurposing LIBs for stationary energy storage leads to a 15% decline in their overall contribution to climate change. Under optimal refurbishment and utilisation scenarios, this environmental benefit can reach up to a 70% reduction in Global Warming Potential (GWP) (Li et al., 2022). Reuse strategies for spent EV LIBs primarily involve remanufacturing and repurposing. Remanufacturing involves refurbishing power LIBs to be used in their original applications (Hua et al., 2021). This process includes several stages: diagnosing the condition of the batteries (Hua et al., 2020), dismantling the BPs (Kaarlela et al., 2024), replacing any damaged cells or modules (Chuang et al., 2024), and reassembling them into new packs (Garg et al., 2020). The economic impact of remanufacturing is notable; it is estimated that between 2020 and 2033, the quantities of spent vehicle LIBs will approach 50% of the new battery demand, with remanufacturing potentially reducing the cost of new LIBs by around 40% (Dobó et al., 2023). Repurposing, on the other hand, involves reconfiguring retired vehicle batteries for secondary life applications, such as stationary energy storage systems, which operate under less demanding conditions than in EVs. This approach extends the service life of LIBs, allowing for additional value extraction from these batteries. Repurposing typically requires the replacement of damaged cells or modules and reconfiguration of the packs to fit stationary applications (Persis et al., 2024). Recent studies highlight that repurposed LIBs can provide reliable and cost-effective storage solutions, with performance often exceeding initial expectations (Steckel et al., 2021). Specifically, NMC batteries exhibit the highest carbon emissions among LIB chemistries when their second-life application is excluded, generating twice the GWP of LMO batteries. However, when integrated into a cascading use system, the environmental impact of NMC batteries aligns more closely with that of NCA variants, though it remains approximately 30-50% greater than that of LMO cells. Notably, the gap in life cycle greenhouse gas emissions between NMC and LMO batteries narrows substantially, from 0.092-0.188 kg CO2-equivalent to just 0.009-0.023 kg CO2-equivalent (Li et al., 2022). Moreover, incorporating second-life batteries into grid-scale energy storage infrastructures supports both grid reliability and improved energy utilisation (Hamdan et al., 2024). Subsequent recycling after secondary deployment can yield an additional 8% to 17% reduction in the carbon footprint associated with LIBs (Tao et al., 2021). These reuse options not only offer environmental benefits by reducing waste and conserving resources but also present economic advantages by lowering the cost of energy storage solutions and extending the lifecycle of battery technologies.

Table 2. A detailed comparison of various battery types based on their specific technical characteristics (Jin et al., 2022; Samanta et al., 2024; Hasselwander et al., 2023; Tognan et al., 2019; Bhowmik et al., 2023; Kannan, 2020).

Full Name	***Chemistry***	***Abbreviation***	***Voltage (V)***	***Energy density (Wh/kg)***	***Cycle life***	***First developed and used***	***Application areas***	***Pros***	***Cons***
Nickel Manganese Cobalt Oxide	$LiNiMnCoO_2$	NMC	3.6-3.7	150-220	1,000-2,000	Company AESC (Automotive Energy Supply Corporation), a partnership between NEC Corporation and Nissan	• EVs • Energy storage system • Power tools • Medical devices	• Optimised performance featuring high energy density and extended cycle life • Highly versatile, meaning it is suitable for a broad application • More cost-effective than pure cobalt-based batteries	• Safety concerns necessitate the use of a Battery Management System (BMS) for optimal performance • Performance may vary depending on the ratio of includes
Nickel Cobalt Aluminium Oxide	$LiNiCoAlO_2$	NCA	3.6-3.7	200-322	1,000-1,500	Tesla, Inc. in partnership with battery manufacturer Panasonic	• EVs with high performance • Industrial applications	• Highly suitable for the long distance which is a preliminary problem of EVs • Offers a long cycle life, though shorter than that of LFP batteries.	• Requiring high cost because of containing cobalt and aluminium • Need highly complex BMS
Lithium Titanate	$Li_4Ti_5O_{12}$	LTO	2.3-2.4	50-90	5,000-10,000+	Altairnano Inc. and A123 Systems	• Electric buses • Solar powered street lighting • Uninterruptible power supplies	• Able to do too fast charging • Exceedingly long lifespan • Extremely safe with outstanding thermal stability	• Too low energy density capacity • Struggles with cost because of the usage of titanium
Lithium Iron Phosphate	$LiFePO_4$	LFP	3.3	90-190	2,000-4,000	A123 Systems	• EVs • Power tools • Medical devices • Solar energy storage	• Overheating risky is restricted well, causing too safe • Quite good lifespan • Consistent thermal attributes	• Low energy density range • Marginally lower voltage • Makes the battery heavier
Lithium Manganese Oxide	$LiMn_2O_4$	LMO	3.7-3.8	100-150	500-1,000	Mitsubishi Motors	• EVs and bikes • Power tools • Medical devices	• Exceptional thermal stability, mitigating the risk of thermal runaway • Strong discharge current capability • More affordable than cobalt-based batteries	• Low lifespan, typically having a less than 1,000 cycles • Lower energy density compared to LCO, NMC and NCA
Lithium Cobalt Oxide	$LiCoO_2$	LCO	3.6-3.7	150-200	500-1,000	Sony Corporation	• Smartphones • Tablets • Cameras • Laptops	• Highly energy density for portable devices • Consistent voltage whilst discharging	• Having short lifespan • Costly due to cobalt • Can tend to be overheating, contributing to increment unsafety under stress

Table 3. Comparisons for the battery cell types with the detailed information.

Battery cell types	*Design and structure*	*Energy density*	*Thermal management*	*Cost and manufacturing*	*Application example*	*Pros*	*Cons*	*Recent developments and trends*
Cylindrical Battery	They feature a coiled configuration housed within a metal cylinder, often made of steel or aluminium. This construction provides strong mechanical resilience, enabling them to endure greater internal pressure and physical stress.	• Usually, with the help of technological improvement, it has reached up to 300 Wh/kg. • Prismatic<Cylindrical <Pouch	The cylindrical form enhances heat dissipation, lowering the likelihood of thermal runaway. However, in larger packs, heat may not be evenly distributed.	• Due to the standardised sizes, having simplify mass production, causing reducing costs • Struggles more complex packing and cooling solutions can increase overall system costs	• Tesla Model 3, Model Y, and older models • Lucid Air sedan • Rivian R1T and R1S	• Robust design • Improved thermal management • Standardised production	• Complex packing • Low energy density	The transition to larger formats such as the 4680 cells, pioneered by Tesla, is underway, targeting increased energy density and lower costs. Key areas of development include advancements in fast charging technologies and enhancements in thermal management.
Pouch Battery	Pouch cells feature a flexible and lightweight design, enclosed in a polymer-aluminium laminate. This construction provides greater design flexibility regarding shape and size, making them well-suited for customised applications.	• Offering the highest energy density value among others • Typically have more than 300 Wh/kg	They are more susceptible to swelling caused by gas generation during cycling, which can impact both safety and longevity. Effective thermal management solutions are crucial in preventing overheating.	• In manufacturing, since it has more complex because of the demand for protective casing and thermal management systems • Nevertheless, the flexible design allows for more efficient space utilisation in BPs, which can mitigate some of these drawbacks.	• Chevrolet Bolt EV • BMW i3 and i4 EV • Audi e-tron series • Hyundai Kona and Ioniq EV model • Kia Soul and Niro EV	• Excellent energy density among others • Flexible design opportunity	• Prone to expansion • demands rigorous thermal management	Significant advancements have been made in integrating solid-state electrolytes within pouch cells to boost safety and energy density. The growing popularity of EVs has increased the demand for larger, more efficient pouch cells, with a focus on extending cycle life and enhancing thermal stability.
Prismatic Battery	Prismatic cells feature a rectangular form with a rigid metal or plastic enclosure, which facilitates effective space optimisation in BPs but may result in increased weight and reduced flexibility.	• Having the least energy density value among others • Nearly 250-280 Wh/kg	They offer superior heat dissipation compared to pouch cells thanks to their larger surface area, yet they still need effective thermal management systems to avoid hotspots.	• Design may be costlier to manufacture due to precise casing and internal component requirements. • The rectangular shape simplifies pack assembly, indicating mitigation of overall system costs.	• BYD Tang and Han EV • Nissan Leaf • Mercedes-Benz EQ series • Volvo XC40 Recharge	• Optimal space usage • Enhanced heat dissipation	• Weightier • Priced at a premium	Studies can involve using advanced materials like silicon anodes to increase energy density. They can also test contemporary casing materials to cut weight and cost while keeping durability intact.

Recycling

Resource extraction from decommissioned LIBs is presently executed using one of three primary methods: pyrometallurgical, hydrometallurgical, and direct recycling processes (Biswal et al., 2024). Each of these methods is essential for the effective retrieval of valuable resources from used batteries, thereby enhancing the sustainability of LIB technology. Pyrometallurgy involves a high-temperature smelting process, typically encompassing combustion followed by separation, to yield a mixed metal alloy containing cobalt, copper, iron, and nickel (Shamsuddin and Sohn, 2024). This method is a proven technique and is commonly used for LIBs, especially those with high cobalt content (Abdalla et al., 2023). A main benefit of pyrometallurgy is that it usually does not need battery types to be sorted first. This makes it a flexible choice for handling different battery materials. However, the alloy that forms often needs more work to separate and clean the metals. This can make the recycling process more complex and expensive. Even with these issues, pyrometallurgy is still a trusted and widely used method for recovering materials from LIBs in industrial era (Leal et al., 2023). Hydrometallurgy, on the other hand, gets the needed metals from cathode material by dissolving them in an acidic or alkaline water-based solution. This method enables the recovery of almost all LIB components with high purity, making them appealing for recycling (Dobó et al., 2023). However, additional steps like concentration and purification are often needed to separate the recovered metals. Unlike pyrometallurgy, hydrometallurgy usually requires sorting battery types before processing, which can complicate and raise costs in the recycling process. Still, its ability to recover metals with minimal environmental impact makes it a promising choice for sustainable LIB recycling. Next, direct recycling involves reusing the cathode and/or anode material from used LIBs thereafter reconditioning (Ahuis et al., 2024). Although this method is guaranteed because it permits for straightforward recovery and reuse of most battery components without extra processing (Mrozik et al., 2021), direct recycling is not yet fully developed as a technology. It is attractive because it could greatly cut down on raw material extraction and processing. However, issues like electrode material degradation during use and differences in battery chemistries have limited its widespread use. More research and development are needed to address these problems and make direct recycling a practical method for recovering LIB materials. Recent life cycle assessment studies conducted by Yang et al. (2024a) have recently conducted life cycle assessments that shed light on the ecological implications of various battery recycling techniques. Their findings reveal that reusing LIBs, particularly in applications such as stationary energy storage or mobile charging units, can lower their GWP by as much as fivefold when compared to direct extraction of materials. Among the primary recycling routes assessed, the direct recycling approach produced the least greenhouse gas emissions, with a GWP measured at merely 0.037 kg CO2 equivalent per kilogram of battery. Crucially, incorporating a second-life phase prior to recycling greatly enhances the environmental advantages, especially in scenarios characterised by frequent use and variable conditions. The study emphasises that fostering second-life deployment, underpinned by robust policies and harmonised testing procedures, could reframe battery recycling as a comprehensive environmental strategy rather than a solely resource-recovery process. Likewise, Jiang et al. (2025) explore the future resource requirements and associate emissions from EV batteries in China, concluding that integrating reuse with recycling could curtail demand for lithium, cobalt, and nickel by up to 67%, 96%, and 93%, respectively, over the 2021-2060 period. Their analysis also suggests that this dual approach could reduce carbon emissions by up to 38%; however, it introduces a possible tension between emissions reduction and lithium supply security, due to delays in material recovery. These insights underscore the importance of carefully balancing extended battery use with timely recycling to maintain both environmental integrity and material availability. Besides these main methods, other technologies are being explored for future LIB recycling. These include biohydrometallurgy (Satriadi et al., 2024), which uses microorganisms to extract metals; plasma-assisted smelting (Kusano and Kusano, 2024), which uses high-temperature plasma to recover metals; oxidation-reduction recycling (Lv et al., 2024), which employs oxidation and reduction to recover specific materials from used batteries; and solvometallurgy, which amplifies the strengths of pyrometallurgy and hydrometallurgy while simultaneously reducing their individual drawbacks (Golmohammadzadeh et al., 2022). Each of these technologies has its own pros and cons and is still in different stages of development. In Table 4, a thorough assessment of both the traditional and innovative recycling methods outlined above is provided. Furthermore, Fig. 10 presents a broad overview of all the recycling technologies discussed in this section. Given the limitations of each recycling method, the final process for LIB material recovery will likely involve a mix of various techniques, integrated into a clear material flow chart to ensure optimal recycling efficiency (He et al., 2021). This comprehensive approach is vital to maximise the recovery of valuable materials from spent batteries while reducing environmental impact (Zanoletti et al., 2024). Ongoing research and development are crucial for overcoming challenges in LIB recycling. As battery chemistries continue to evolve, recycling facilities will need to adjust their operations to handle new materials and technologies. This demand for continual adaptation underscores the importance of flexible and innovative recycling strategies for the future of sustainable energy storage.

Fig. 10. All classic and pioneering processes in recycling technologies.

Table 4. Comprehensive review on general and contemporary recycling technologies for LIBs (Kusano and Kusano, 2024; Lv et al., 2024; Zanoletti et al., 2024; Noudeng et al., 2022).

Process category	*Depiction*	*Benefits*	*Drawbacks*	*Implementations*	*Regularly handled materials*	*Ecological outcomes*	*Financial aspects*	*Technological proficiency*
Pyrometallurgical	Involves high-heat procedures to liquefy and isolate metals from battery components	• Effective in extracting metals • Proven technology	• Elevated energy use • Risk of hazardous emissions	Widely employed for mass metal recovery	Combined battery elements	• Notable impact • High emission levels	• Major energy cost • Prevalent usage	• Advanced • Widely implemented
Hydrometallurgical	Implements aqueous leaching to recover metals from battery materials	• Consumes lower energy than pyrometallurgy • Provides selective extraction	• Generates a significant amount of liquid waste • Slower processing time	Frequently used for the extraction of lithium and cobalt	• Lithium substances • Cobalt solutions	• Intermediate • Involves handling chemicals	• Reasonable expense • Efficient	• Well-established • Broadly adopted
Direct recycling processes	Reuses battery components or materials with minimal processing	• Keeps the material structure intact • Potentially budget-friendly	• Confined to specific battery models • Technology is still evolving	• Innovative technology • Prioritises material preservation	• Battery electrodes • Supporting materials	• Low to moderate • Dependent on the method	• Variable • Based on technology	• Emerging field • Demands significant research
Biohydrometallurgy	Applies biological techniques, such as microorganisms or enzymes, to recover metals	• Green technology • Requires low energy	• Sluggish and less efficient • Problems with scalability	• Advancing research • Specific niche applications	• Difficult-to-process ores • Subpar materials	• Low impact • Sustainable	• Inexpensive • High return on investment potential	• Experimental • Developing
Plasma-assisted smelting	Utilises plasma arc technology to extract and recover metals from battery materials using high-energy plasma	• Excellent recovery rates • Suitable for various metals	• Energy-intensive • Technologically complex	Suitable for the extraction of precious metals	Precious metal concentrates	Risk of elevated emissions	• Premium cost • High-value metal extraction	• State-of-the-art • Established within specific industries
Oxidation-reduction recycling	Leverages oxidation-reduction reactions for the extraction and recovery of metals from battery waste	• Specialised in recovering specific metals • Involves selective methods	• Demands exact control • Potential for chemical risks	Tailored for specific metal recovery applications	• Dissolved metals • Extracted from battery waste	• Intermediate • Requires chemical management	• Moderate cost • Specialised	• In progress • Focused on niche areas
Solvometallurgy	Uses solvent extraction with ionic or deep eutectic solvents to extract and recover metals	• Selective process • can be designed to be eco-friendly	• Costly solvents • Concerns with solvent stability	• Pioneering research • Targeted at valuable applications	• Battery electrolytes • Metal solutions	• Low environmental impact • Pioneering	• High cost • Potential for efficiency gains	• Evolving • Currently under investigation

Landfilling

Landfilling continues to be the dominant method for disposing of municipal solid waste and hazardous waste worldwide (Vaverková, 2019; Fazzo et al., 2023). Historically regarded as an economical and environmentally acceptable option, landfilling has evolved significantly over recent decades. These advancements include enhancements in planning, design, operation, closure, and post-closure management of landfills, along with improved monitoring and more effective economic utilisation strategies. Despite these advancements, environmental challenges remain, especially in areas where outdated practices persist due to limited resources, lack of access to innovative technologies, and low public awareness (Noudeng et al., 2022). In developing countries, shortcomings in waste management result in improper waste handling, including the unsegregated disposal of hazardous materials and general waste in open-loop landfills. This practice poses serious threats to human health and environmental safety (Ismail and Latifah, 2013), particularly given the low recovery rates and insufficient infrastructure for hazardous waste management. EOL LIBs from small portable devices and electronic waste (e-waste) are often discarded in landfills, leading to significant environmental risks (Ferronato and Torretta, 2019). The consequences of landfilling spent LIBs are severe. Acid-producing microorganisms in landfills can corrode the aluminium casings of batteries, causing toxic metals like cobalt, nickel, and manganese to leach into the soil and groundwater. This contamination compromises environmental safety and poses serious risks to public health (Or et al., 2020; King and Boxall, 2019). Furthermore, when LIB electrolytes react with water, they can release harmful gases such as hydrogen fluoride into the atmosphere, further exacerbating pollution (Han and Jung, 2022). When LIBs containing lithium plating are disposed of in landfills, the lithium can react violently with water, causing serious fires and explosions (Sommerville et al., 2020). In addition to these concerns, landfill fires, both surface and subsurface, present a significant threat. These fires are often triggered by the spontaneous auto-ignition of methane, and LIBs buried in landfills can amplify and prolong these fires due to their flammable electrolytes (Yang et al., 2024a). The UK's Environmental Services Association found that of 670 fires from April 2019 to March 2020, 145 were caused by LIBs, and another 112 were suspected to involve them. Many garbage trucks caught fire because of improper LIB disposal. In 2021, the UK waste industry had 201 fires related to LIBs. The California Product Stewardship Council reported that LIBs caused 40% of fires at waste management sites (Chen et al., 2022b). Such fires not only release toxic gases, including polycyclic aromatic hydrocarbons, volatile organic compounds, and heavy metals, but they also pose long-term environmental risks by contaminating nearby water bodies (Szulc et al., 2024). Given the rapid growth of the EV market, the inadequate facilities for treating EOL batteries raise concerns about the future disposal of large LIBs. While these batteries are typically recovered for valuable metals, residue waste from the recycling process, such as bottom ash, is often landfilled, leading to further environmental burdens (Mathur et al., 2019). Current evaluations of EOL LIBs employed in small-scale energy storage applications reveal that over 97% of their total mass, including cells, enclosures, bus bars, and ancillary parts, continues to be sent to landfill due to inadequate recovery processes and inherent design flaws. Notably, more than 31.5 kilograms of lithium-ion cells, which account for over 60% of the system's weight, are disposed of without any recovery, along with significant volumes of structural components such as casings and cell holders. This approach not only results in the irreversible loss of critical materials but also heightens the environmental hazards linked to the landfill disposal of potentially dangerous battery constituents. These findings highlight that even well-monitored academic or prototype projects remain vulnerable to the broader systemic failures in EOL battery management (Sen et al., 2024). To mitigate these risks, alternative strategies such as complete discharging, removal of flammable electrolytes, and the use of additional liners to immobilise hazardous content must be considered seriously (Yang et al., 2024a). In conclusion, the environmental and safety risks associated with landfilling LIBs are substantial. Addressing these challenges requires enhanced waste management practices, stricter regulations, and the development of infrastructure capable of handling the increasing volume of LIBs to prevent long-term environmental damage and ensure public health safety.

Illegal disposal

The illegal disposal of LIBs is becoming a significant environmental issue (Sannagowdar and Nataraj, 2024). The use of these batteries is rapidly increasing due to the rise of EVs, mobile devices, and renewable energy storage systems (Rangarajan et al., 2022). However, this growth also raises concerns about proper disposal at the end of their life cycle (Lima et al., 2022). Improper disposal methods can seriously harm both the environment and human health. If LIBs are not recycled properly, toxic metals like lithium, cobalt, and nickel can leak into the soil and water (Christensen et al., 2021). This can degrade soil quality, contaminate water resources, and harm ecosystems (Sobianowska-Turek et al., 2021). For instance, high levels of cobalt can cause severe toxicity in aquatic ecosystems, threatening biodiversity (Costa et al., 2022). Additionally, the accumulation of these metals in crops intended for human consumption can lead to long-term public health issues (Hossain et al., 2023). Illegal disposal often involves exporting used batteries to developing countries, where low-cost methods that fail to meet environmental standards are used. This is common in regions like Africa and South Asia (Werner et al., 2020). In countries like China and India, workers in informal recycling facilities face significant health risks due to inadequate protective gear when sorting batteries (Bansal et al., 2023). These risks include heavy metal poisoning, respiratory diseases, and skin conditions (Łukasz et al., 2023). The economic impact of illegal disposal is further significant (Sun et al., 2021). It can lead to higher cleanup costs and harm local economies by damaging the environment. Moreover, disrupting proper recycling processes prevents valuable metals like lithium and cobalt from being recovered, making resource use less efficient (Meegoda et al., 2024). To address these issues, a global regulatory framework is needed (Christensen et al., 2021). This framework should ensure traceability throughout the entire life cycle of batteries and impose strict penalties to deter illegal disposal. Developed countries must also enforce tighter controls on the export of LIBs, particularly monitoring those sent to developing countries. Training and technology transfer programs for developing countries can help set up environmentally friendly recycling facilities (Chigbu, 2024). For instance, international cooperation in establishing modern recycling technologies can reduce environmental damage and boost local economies (Afroze et al., 2023). Developing methods to extend the life cycle of LIBs is also crucial (Ruan et al., 2023). Reusing or refurbishing EOL batteries can lower the demand for new raw materials and reduce illegal disposal rates (Zhao et al., 2021b). Designing batteries to last longer and be easier to recycle is important (Hossain et al., 2023). For instance, modular battery designs can facilitate easier repairs and reuse. Finally, consumers need to be informed and encouraged to deliver batteries to proper recycling points. Educating them about the importance of recycling and the process involved can promote correct disposal methods (Mathew et al., 2023). Recycling incentive programs can also motivate consumers to participate actively (Yan, 2024). These measures will help reduce the environmental impact of LIBs and prevent illegal disposal.

ELECTRIC VEHICLES USING LI-ION BATTERIES

In this section, Li-ion batteries used in BEVs are classified into two main categories: moving and stationary systems. Then, based on their purposes, several subcategories are represented and explained. Below is the classification of those discussed in this paper.

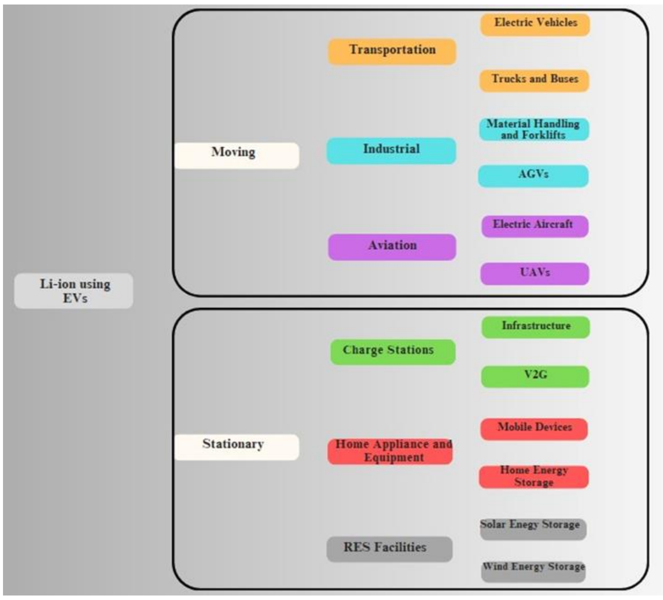

Fig. 11. Classification of EVs using LIBs.

Moving

Transportation system

LIBs are the main power source for EVs, including automobiles, buses, and trucks. As a consequence of their high energy density and overall efficiency, they become a suitable and proper selection to be used in automobiles (Nykvist and Nilsson, 2015; Lutsey, 2015). As the effects of fossil fuel use on the environment and people become more noticeable and understandable, and the reactions and actions of governments and social organisations on this issue increase, today's giant automobile manufacturers such as Tesla, Nissan, Toyota, and BMW have focused on EVs and made large investments for LIB technology, especially for performance and range improvements (Harlow et al., 2019). As mentioned above, the impact of fossil fuels on GHG emissions and the necessity of reducing these emissions are the driving factors in the development of EV technology (Hawkins et al., 2013).

Electric vehicles

LIB technologies are used in most of the EVs used in the transportation sector. The main reason for this is that LIBs are more convenient in terms of energy density and life cycle. Thanks to these features of LIBs, users are provided with shorter charging times and an increased driving range of the EV (Wang et al., 2016; Scrosati, 2000). As explained, short charging time is an important criterion for consumers, and this shows that charging infrastructures should be improved in terms of efficiency and the consumer should not have problems reaching the charging station, meaning a widespread charging infrastructure is required (Neubauer and Wood, 2014). On the engineering side of this technology, there are parts, such as thermal issues, that still need to be developed and managed properly during the operation of the product. The main reason for these problems lies in the fact that LIBs have various thermophysical properties, such as overheating due to discharge and charging during short periods of use. In order for these problems to be experienced as little as possible and not to be reflected on the consumer as much as possible, it is a necessity to develop appropriate BTMs and integrate them into EVs (Pesaran, 2002).

Electric-powered trucks and buses

Conventional buses and trucks show remarkable negative effects in terms of noise and air pollution, especially in urban areas, therefore, electric versions of these vehicles have begun to increase their popularity (Lajunen, 2014). Due to the sector in which they are preferred, such vehicles require dimensionally larger and higher performance batteries in terms of battery capacity and power. In this context, LIBs may be preferred in such EVs as they are convenient and efficient for multi-assembly design and integration (Lutsey and Nicholas, 2019). In addition to the mentioned advantages, the requirements that must be met for the operation of these batteries are inflexible and must be accessed without compromise (Hannan et al., 2017). Due to the purpose of the development of these EVs, they generally require high power and torque output as well as a frequent charging cycle. Moreover, if these demands are not controlled regularly, the product life cycle will be negatively affected and a process towards degradation will begin.

Industrial machinery

There are automation-controlled vehicles (usually robots), manufacturing machines (such as Computerised Numerical Control machines) and various parts of them that are powered by LIBs, which today's industry also benefits from. Compared to traditional LABs, these batteries and the vehicles in which these batteries are integrated with the industry are in a more advantageous position in terms of being less harmful to the environment and consumer usability. The control mechanisms of EVs in the industry also respond faster due to their design and control algorithms compared to mechanical ones. This ensures continuous efficiency by reducing downtime, which is extremely important for manufacturing or machining, and thus unnecessary costs are prevented (Pillot, 2017; Scrosati and Garche, 2010). Finally, the use of LIB integrated EVs in the industry facilitates the transition to sustainable and environmentally friendly practices.

Material handling equipment and forklifts

In addition to the previously mentioned advantages of forklifts and other material handling equipment using LIBs, these batteries offer high power density and fast charging (Ordoñez et al., 2016). In addition, these vehicles play an important role in minimising inactivity periods by enabling continuous operation, thus providing various advantages, especially in the field of logistics and workplaces such as warehouses (Pillot, 2017). In addition to the advantages discussed, the requirements of the operating conditions and environment, including discharging and charging at a frequent frequency, may cause some thermal problems, such as overheating. At this point, it is important to select and integrate the appropriate BTM for both the vehicle's ability to keep operating without interruption and for safety reasons (Hannan et al., 2017).

Automated guided vehicles

With the development of today's industry, important steps are being taken in saving time. The use of automated guided vehicles (AGVs) has also become increasingly widespread in the manufacturing industry and distribution centres (Viswanathan et al., 2014). LIBs provide the power and energy density required for these vehicles to perform their functions continuously and completely, which again increases productivity and reduces labour-related costs. Some of the important technical requirements in AGVs are to establish a harmonic balance between energy density and power output and to ensure stable and reliable performance in situations where fluctuating power is encountered (Scrosati and Garche, 2010).

Aviation industry

Although it has not yet spread to all branches of the aviation industry, research and development efforts are ongoing, especially for unmanned aerial vehicles, where LIBs will be used in the future. Except for small drones, fossil fuel internal combustion pistons and jet engines are generally used in aircraft. These engines also have a negative impact on performance by reducing the power-to-weight ratio of the aircraft because of the materials they are made of and their complexity. Therefore, providing the power demand from batteries will improve this ratio (Viswanathan et al., 2014). Research in this field and prototype development of electric aircraft have been scrutinised by major manufacturers such as Boeing and Airbus (Dai and Zhu, 2024).

Electric aircraft

One of the main purposes of researchers developing electric aircraft is to reduce fuel consumption and, at the same time, prevent the release of harmful gases into the atmosphere (Viswanathan et al., 2014). In this way, the concerns of environmentalists regarding this issue will be resolved. At this point, it is an advantage that LIBs are suitable for short-distance or regional flights without sacrificing performance, thanks to their high energy density. The main goal of the ongoing research is to further improve parameters such as performance and range (Dai and Zhu, 2024). Just as mentioned in the industrial EVs section, the operating conditions of these batteries used in aircraft are challenging. In particular, in accordance with the strict safety rules in aviation regulations, these batteries must be protected from overheating, and the resulting thermal runaway and the safety of the passengers must not be at risk (Viswanathan et al., 2014).

Unmanned aerial vehicles

Nowadays, various sectors use drones for agriculture, photography and distribution purposes (Scrosati, 2000; Viswanathan et al., 2014). When looking at these areas, it is clear that LIBs provide advantages in terms of energy density and weight. Some studies have emphasised that these batteries can extend flight time and improve payload capacity (Viswanathan et al., 2014). Since the standards in the aviation industry are high, requirements like flight time and uninterrupted performance under all environmental conditions are the challenges faced by researchers in the field of unmanned aerial vehicles (Scrosati, 2000).

Stationary

Charging stations for electric vehicles

Effectively controlling and managing long-term charging operations and ensuring a regular supply of power to the battery are the most important requirements in EV charging stations (Neubauer and Wood, 2014; Lund and Kempton, 2008). These batteries also have the capability of a short charging time and can utilise renewable energy sources, as stated by Hesse et al. (2017).

Infrastructure for rapid charging system

For EVs using LIBs to be quickly and widely accepted by consumers and to mitigate technical prejudices against these vehicles, it is significant to keep the charging time as short as possible and to have advanced rapid charging infrastructure for this purpose (Neubauer and Wood, 2014; Hesse et al., 2017). Thanks to advanced infrastructures, the energy required for high-power charging stations is stored efficiently; thus, saving time that satisfies the consumer is achieved (Lund and Kempton, 2008). In this context, another important feature of LIBs is that they are used as the energy storage medium in these stations. At this point, since fast charging and large amounts of energy are involved, overheating resulting from thermal issues can lead to more dangerous situations, so the integration of thermal management systems in these infrastructures becomes more important (Pesaran, 2002).

Vehicle-to-grid systems

As the name suggests, vehicle-to-grid systems are designed to transfer power from vehicles to the grid during possible high energy demand periods. These systems not only positively affect the stability of the grid but also decline the need to install other power plants (Lund and Kempton, 2008; Kempton and Tomić, 2005). Again, in this area, LIBs are superior to other battery types as they have capabilities such as fast response and high energy efficiency (Scrosati, 2000). In vehicle-to-grid systems, as in other EV infrastructures, it is a technical requirement to keep the performance at the desired level at all times. However, having a power supply in both directions is another matter, so regular management of the operation is required (Kempton and Tomić, 2005).

Home appliances and equipment

Today and in the past few decades, LIBs have been used in almost all mobile-portable devices such as mobile phones, laptops, tablets, walkie-talkies and calculators (Blomgren, 2017; Nitta et al., 2015). The main reasons why LIBs are preferred are that they have a long lifecycle, dimensionally convenient and can meet the charging and power needs of a mobile device for a long time (Blomgren, 2017). Extending the lifecycle of these batteries used for mobile purposes, eliminating safety concerns, and introducing a more consumer-friendly approach by reducing the discharge time are among the primary objectives of the research still being conducted (Nitta et al., 2015).

Home energy storage systems

Home energy storage systems (HESSs) make use of LIBs in order to have the capacity to store energy that is generated from renewable sources, such as solar panels (Luo et al., 2015; Zakeri and Syri, 2015). Moreover, other important advantages are extending the lifespan of household appliances by providing a regular current or as an alternative power source in cases including a power outage, making the power input to home appliances healthier (Dunn et al., 2011). Since HESSs are used directly in homes, specifically in living spaces, the most critical technical requirements are to ensure safety, maintain uninterrupted performance, and prevent thermal issues to avoid negatively impacting living conditions (Luo et al., 2015).

Facilities for renewable energy sources

Especially in the last few years, the application of renewable energy systems such as solar panels and wind turbines for home use has become a trend. However, it is a necessity to store this energy so that its usage is not restricted only to sunny or windy weather and to utilise these resources at any time. Thanks to these batteries, the grid system can be stabilised and provide a more regular current in case the electrical energy coming from the city grid remains fluctuating and low (Zakeri and Syri, 2015; Dunn et al., 2011). It has also been stated in other studies that LIBs are an essential and very accurate choice for renewable energy storage (Luo et al., 2015).

Solar energy storage

Solar energy systems can generally produce electricity during the day and in relatively clear and sunny weather. If the electricity consumption is less than the electricity produced in the solar system, this energy can be stored in LIBs for use at night or in unsuitable weather conditions (Luo et al., 2015; Zakeri and Syri, 2015). Thanks to these storage systems, the efficiency and reliability of the solar energy system are improved, making it a powerful option for commercial or normal use (Dunn et al., 2011). The most important technical issue in solar systems is a well-engineered optimisation that will ensure synchronised operation of energy storage times or direct energy flow, taking into account weather conditions and energy needs (Luo et al., 2015).

Wind energy storage

Similar to solar energy storage systems, the same logic applies to wind energy storage. Excess electricity production can be stored in LIBs and used in windless weather or power outages (Luo et al., 2015; Zakeri and Syri, 2015). The main difference that distinguishes wind energy storage from others is that the wind regime is generally not regular and exhibits chaotic behaviour. For this reason, with a well-designed storage system, the requirements in terms of safety and performance are met by providing regular electric current, provided that the charging and discharging periods of the batteries are regularly controlled (Luo et al., 2015; Dunn et al., 2011).

BATTERY THERMAL MANAGEMENT SYSTEMS

Using a battery powered EV requires several components and subsystems to ensure a safe and effective operation for a long period. Safety-based issues may include thermal runaways, property failure, explosions, etc. (Paneerselvam et al., 2024). BTMS play a pivotal role in the operation of EVs and HEVs. Their primary function is maintaining and regulating the BP's temperature within a specified range to ensure optimal performance, efficiency, and longevity whilst prioritising safety. As the temperature reaches higher values, the safety limits of the battery working environment may be exceeded, resulting in the power battery respect to the failure of a large area, occurrence of the thermal runaway danger and unexpected and rapid explosion of the battery. Thus, it is crucial to keep the battery working temperature under control within the aim of the safety and best work, for rejection of the battery. The idea behind the integration of a BTMS is to reject any heat and overcome the non-optimal temperature range issues caused by temperature gradients that are affecting the EV's optimum performance range (Pesaran, 2002; Thomas and Newman, 2003). It can be basically proven by the 2nd law of thermodynamics in which heat generation-entropy relation is explained as if a system heats up for different reasons, molecules of that object or working fluid become disordered (Cengel and Boles, 1989). Factors that will lead to heat generation within battery cells are chemical reactions within the battery, reversible entropy, and some other physical and chemical phenomena (Thomas and Newman, 2003).

Process of heat generation inside the battery

The heat produced within the battery due to various physical and chemical reasons mentioned before, first passes through the electrolyte and reaches the shell or battery wall, and from there, it is transferred to the external environment, that is, the environment, through various heat transfer methods and most of this heat transfer occurs through conduction and convection, while heat transfer by radiation is negligible compared to others (Panchal et al., 2016). The mathematical modelling of heat production in the battery and its transfer to the external environment includes the mentioned heat transfer concepts and the heat flux within the battery (Wu et al., 2024b). As discussed in the sections above, the main goal of this paper represents the assignment of cooling systems to different types of BEVs. As a BEV is used for a period of time, it physically discharges, and it is recharged again for reuse. During those processes, different types of heat are generated. As a result of electrochemical reaction polarisation, an activation of irreversible heat is generated (Smith and Wang, 2006). Also, ohmic losses take place due to the joule heating and since there will be an entropy change in the process of charging and discharging, reversible reaction heat is observed (Peng and Jiang, 2016). Development and integration of a BTMS system into a LIB require a proper understanding of how heat is generated inside a battery cell because of the strong relation between its performance and temperature (Hallaj et al., 1999). Electrochemical reaction rate with respect to temperature and time, and also the flow of electrons forming a current, are the specific issues that need to be understood. That relation is explained by Gu and Wang (2000), in which the heat generation rate is formulated as a function of the quantities mentioned.

$$\dot{Q} = I\left(U - \dot{V}\right) - I\left(T\frac{dU}{dT}\right) \quad (1)$$

In the formula above, heat generation rate, electric current, open-circuit voltage and cell voltage are represented for $\dot{Q}$, I, U, and $\dot{V}$, respectively. The term $\dot{Q}$ is in watts, since it represents the J/s whilst the first term on the right-hand side gives the losses in the cell due to the resistances and the second term includes the relation of reversible entropic heat and electrochemical reaction. As explained before, heat generation occurs in several ways and in the case of being unable to release the heat from the battery, its performance gets lower in terms of capacity and power (Bandhauer et al., 2011). For a better understanding of different heat generation mechanisms, some models have been established. Those are equivalent circuit model (Liu et al., 2014), electrochemical model (Bahiraei et al., 2017), and electrothermal model (Vertiz et al., 2014), and each considers different physical and thermal quantities to explain the heat production inside the batteries.

Dependence of performance on heat generation

A decrease in the battery's performance can be explained by the temperature rises due to several reasons investigated above, the materials inside the battery cells become an inactive form since power is generated by different electrochemical reactions and those materials are also chemicals which lose their specific properties with thermochemical and thermophysical conditions as resulted in impedance in LIBs (Joshi, 2016). It is not accurate to assume that as battery capacity increases, power decreases. The relationship between capacity and power is complex because capacity depends on various factors, including the battery materials, operating conditions (such as temperature), and the number of charge cycles. However, the relation between capacity and voltage range is strongly dependent on the optimum temperature range. Accordingly, in case the temperature shifts to lower or upper from the optimum range, a critical capacity loss can be observed (Ramadass et al., 2002; Shim et al., 2002; Liu et al., 2010). The capacity fade of LIBs is an important phenomenon, but power fade should also be considered. In the LIB related studies, significance of power fade is discussed in detail and functioned by temperature and depth of discharge, which basically represents the ratio of discharged power of the battery to the overall capacity (Belt et al., 2005). Besides, thermal runaway is another issue that can result in dangerous situations, flame or explosion (Balakrishnan et al., 2006). Considering all these studies, created models and analyses, it is clearly understood how important BTMs are in terms of performance, safety and battery life. According to studies conducted (Amer et al., 2024), some phenomena may be faced at different temperatures which are dendrite formation and lithium plating below 0°, energy and power fade from 0° to 15°, mismatch of charge between 15° and 35°, considered as optimum range, and above this temperature, accelerated ageing and thermal runaway issues as shown in Fig. 12.

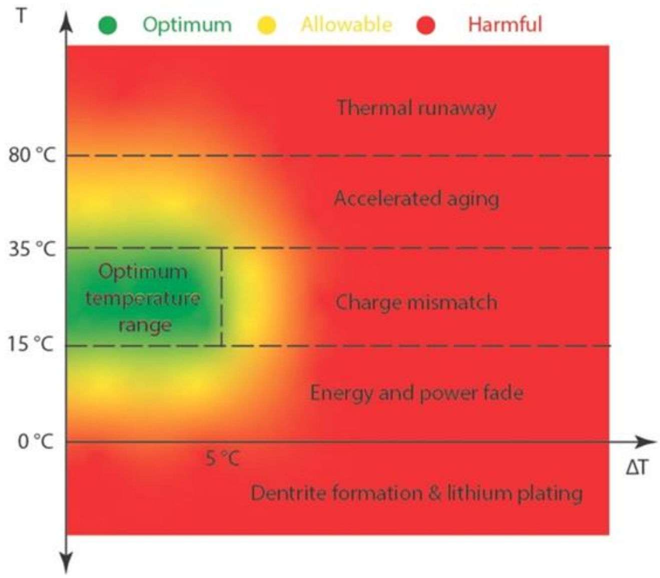

Fig. 12. Different issues LIBs may experience at various temperatures (Amer et al., 2024).

Classification methods of battery management systems

The process of rejecting heat from the battery systems is classified into four categories in general: heat transfer medium, power consumption, and contact between the coolant and battery surface (Direct or Indirect cooling) (Paneerselvam et al., 2024). Further, it can be classified based on the configuration of cells arranged in a BP. Classification based on medium includes four different types in general: air cooling, liquid cooling, heat pipe (HP) cooling and PCM cooling (Rao and Wang, 2011). On the other side, power consumption-based classification means whether the system consumes power or not. This sub-classification is divided into two main ways as well: active and passive cooling.

Active cooling basically means that the cooling process is processed by an external energy source work input or methods that carry out heat transfer by employing a source of energy (Sabbah et al., 2008). In order to apply such a system, several turbomachinery devices can be used, like fans, pumps, or compressors. In thermal management systems that work with passive cooling, the heat discharge mechanism is carried out by medium conditions, provided that the appropriate design and heat transfer environment is provided.

In addition to those main ways of cooling, hybrid systems may take place as the other principle of cooling (Yamada et al., 2017). Direct cooling BTMS involves circulating the cooling medium directly over or through the battery cells to absorb and transfer heat away from the battery whereas indirect cooling BTMSs aim to prevent direct contact between the cooling medium and the battery surface (Rallabandi and Selvaraj, 2024). Each system has advantages and disadvantages compared to the others. Therefore, in order to make a proper decision, the power demand and capacity of BEV should be estimated precisely. Based on the studies about BTMSs with specific classification methods, a generalised classification scheme can be represented as follows.

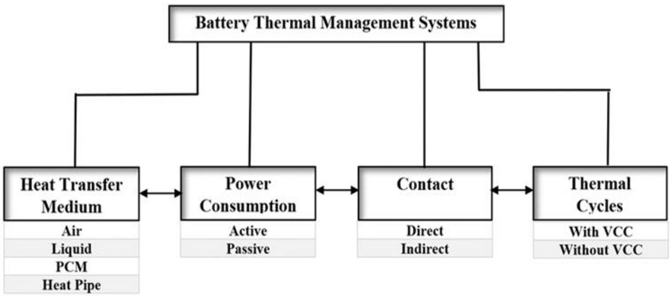

Fig. 13. A general classification of BTMSs according to different parameters.

As can be seen from Fig. 13, the classification of BTMSs is divided into four main parameters. However, it is important to state that each sub-class can be linked to another. For instance, a BTMS contain a Vapour Compression Cycle (VCC), which means the system has active cooling since a work input is required for the compression process. Except for this classification, detailed explanations are made based on BTMS's type of use. To give an example, a coolant can be used as a heat transfer medium, and that system may have a VCC requiring a compressor work subtitled under active systems.

Active battery management systems

Active cooling methods exploiting an external power source predominantly consist of air cooling and liquid cooling systems apart from other methods (e.g. thermoelectric cooling, immersion cooling and refrigeration cooling). This section reviews previously mentioned cooling methods and heat dissipation capability in different environmental conditions with respect to various battery cells based on recent studies in the efficiency performance development of BTMS.

Air cooling

Air cooling is the most traditional approach when it comes to cooling. This method of cooling has been developed thoroughly and is vastly applied in commercial applications. For instance, the Honda Insight and Toyota Prius HEVs redirect the pre-conditioned cabin air into the BP for cooling (Kelly et al., 2002). Air is inherently used as the thermal medium in air systems. The intake air can be drawn directly from the atmosphere, the cabin, or from another pre-conditioned source, such as a heater or evaporator. The former is termed a passive air system, whereas the latter is termed an active air system. An active air system is limited to 1 kW of air conditioning power whereas a passive air system can provide several hundred watts (Ladrech, 2010). Both systems are, by definition, forced air systems due to their nature of being driven by an impeller device. Both systems have low manufacturing costs due to the simple structure when compared to other cooling systems. This, however, leads to defects in poor cooling effect and slow cooling speed, resulting in insufficient heat dissipation of the EV battery modules. To address these challenges, various design innovations aim to enhance the effectiveness of air-based cooling systems. Shen et al. (2023), for example, propose a revised Z-shaped air cooling configuration with an inclined structure that promotes improved airflow. This design lowers the BP's peak temperature from 38.15°C to 34.14°C and achieves a 23.9% enhancement in temperature uniformity. By fine-tuning the channel angle and width, the study shows that such structural modifications considerably boost the heat dissipation rate, thereby ensuring more reliable thermal control. As explained before, active methods require a power input to reject the unexpected heat from the module, by using several machines such as fans to feed enough cooler air to the module as well, as represented in the schematic in Fig. 14 (Rao and Wang, 2011), while passive cooling needs no power consuming machines, shown in Fig. 15 (Mali et al., 2021). In this regard, Chen et al. (2024) introduce an adaptive control approach within a parallel air-cooled architecture, which intelligently alternates between J-type, U-type, and L-type airflow patterns. This system continuously adjusts the flow direction according to real-time variations in cell temperature, ensuring that temperature deviation remains under 0.5 K while improving cooling efficiency by over 67% across different discharge rates and ambient conditions. In parallel, recent studies such as that by Wankhede et al. (2025) demonstrate that combining high-velocity airflow with customised channel geometries successfully maintains battery temperatures within the optimal range of 30-40°C. Using CFD simulations alongside experimental validation in student EVs, their research confirms that air-based cooling solutions can deliver thermal stability when supported by precise parameter tuning and strategic structural design. Their results also show that an inlet air speed of 17 m/s provides ideal cooling conditions, effectively minimising thermal stress throughout the BP.

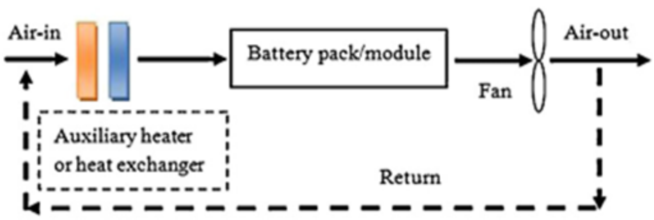

Fig. 14. Active air cooling (Rao and Wang, 2011).

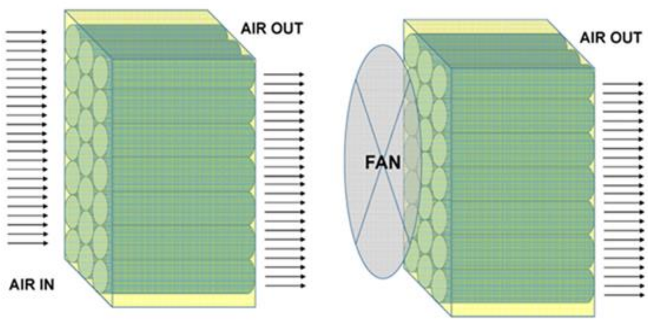

Fig. 15. Passive and active air cooling strategies, respectively (Mali et al., 2021).

Liquid cooling

In addition to the air cooling, liquid cooling method, which is more effective in terms of accommodating the higher energy density and heat flux diffusion. As stated by Kim et al. (2019), liquid cooling is one of the most widely used techniques in battery cooling applications. It can be classified into three categories (Kim et al., 2019):

- Immersing cooling: modules are directly immersed within a dielectric fluid.
- Direct cooling: there is direct contact between the battery surface and heat transfer fluid (HTF). The battery surface is in direct contact with the HTF.
- Indirect cooling: separate piping, cooling plate or a fluid jacket is mounted near each battery cell.

When compared to the air-cooled methods, liquid cooling has several advantages in terms of heat diffusion capacity and observable cooling effect. On the other side, requirements for additional components (heat exchangers, pumps, etc.) give rise to a more complicated structure, production and maintenance costs to increase, and secondary losses mostly on the basis of the 2nd law of thermodynamics (Cengel and Boles, 1989). Recent studies further affirm the efficacy of liquid cooling methods. For example, Sadeh et al. (2024) numerically investigate a hybrid system that integrates both direct and indirect cooling approaches using water and HFE-7100. Their findings indicate that a counterflow configuration can lower the peak battery temperature to below 32.15°C and restrict temperature variation to 3.04°C. The addition of indirect cooling tubes within a direct flow arrangement reduces peak temperatures by up to 8.05°C and thermal non-uniformity by 1.55°C at an inlet flow velocity of 0.1 m/s. Similarly, Feng et al. (2024) optimise liquid cooling parameters, such as channel width (15 mm) and spacing (115 mm), employing a multi-island genetic algorithm. Their enhanced aluminium liquid cooling plate decreases the maximum temperature by 0.274 K and the temperature difference by 0.338 K while achieving energy savings of up to 37.87% through regulated coolant temperature and flow rate. In another approach, Wu et al. (2024a) propose a variable heat transfer path plate design featuring grooves to rearrange thermal pathways along the battery surface. This innovation reduces the surface temperature difference by between 22.7% and 25.4%, depending on discharge and flow rates. Although the maximum temperature improvement is minimal, the variable heat transfer path strategy significantly enhances temperature uniformity across the BP. In practical applications, liquid cooling-involved BTMS systems have been implemented in commercial vehicles such as the Tesla Model S and 3, BMW i3 and i8, and Chevrolet Volt (Wu et al., 2019; Park and Jung, 2013). Water (Gharehghani et al., 2022), a mixture of ethylene glycol and water (Jarrett and Kim, 2014), a deionised form of water (Gou and Liu, 2019), and nanofluids (Wiriyasart et al., 2020) are some of the liquids utilised as a coolant for indirect cooling methods, while direct cooling requiring direct contact, mineral oils (Hosseinzadeh et al., 2017) can be used. A representative schematic explaining the liquid cooling method (Troxler et al., 2014), in which coolant liquid passes from the BP, then pumped into a heat exchanger to be cooled again by air, is below in Fig. 16.

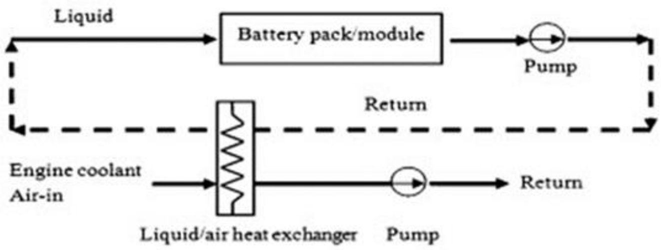

Fig. 16. Active moderate cooling (Rao and Wang, 2011).

Thermoelectric cooling system

Regulation of the battery cell temperature plays a vital role and is progressed with conversion between electrical energy and thermal energy by thermoelectric modules, and the whole system is defined as thermoelectric cooling system (TCS), a type of BTM. By keeping the temperature in an optimal range through TCSs, control of safety issues, an extended lifecycle, improved performance and prevention of overheating and overcooling are achieved (Rallabandi and Selvaraj, 2024). In practice, thermoelectric modules are installed on one or more sections of the battery cell and operate by transferring heat from the cold side to the hot side, keeping the BP within a designated temperature range. These configurations may include various supporting elements, such as heat sinks, blowers, and holders, as illustrated in Fig. 17 (Lyu et al., 2019; Troxler et al., 2014). However, relying solely on TCSs in BTMSs results in low thermal efficiency and requires additional energy for operation, which ultimately reduces BP efficiency. Therefore, integrating TCS with other cooling methods addresses these challenges and maintains performance and other criteria at acceptable levels. This hybridisation, however, incurs increased system complexity and additional power consumption, potentially impacting the overall energy yield of the battery system (Kim et al., 2019). To enhance the overall control strategy in such systems, Wang et al. (2024b) introduce a model predictive control-based thermoelectric cooling BTMS using MATLAB/Simscape, demonstrating significant improvements over traditional PID controllers. Their approach achieves a 35.17% faster response time and lowers energy consumption by 28.65% under constant current conditions at 2C. Furthermore, their control algorithm effectively manages load variations and enhances thermal stability, indicating that predictive control mechanisms could considerably boost TCS efficiency in dynamic operating scenarios. A similar advancement is noted by Cui and Jiang (2024), who develop a nonlinear model predictive control strategy alongside a high-precision thermal model based on spectral methods, enabling more accurate and uniform temperature regulation. Their findings validate the effectiveness of employing advanced control schemes in thermoelectric cooling-based BTMS designs, particularly in mitigating thermal safety risks during real-time operations. While control strategies are crucial, the design parameters of the thermoelectric modules themselves significantly influence performance outcomes. Bhattacharyya et al. (2025) explore these factors for light EVs and show that optimising pellet height in thermoelectric modules directly impacts cooling capacity and energy consumption. Their multi-objective optimisation framework results in a 5.89% reduction in power usage compared to commercial thermoelectric modules, highlighting the necessity for application-specific designs rather than generic units. In more complex configurations, hybrid systems incorporating PCM, porous media, and thermoelectric modules have been studied for their synergistic advantages. Rahmani et al. (2024) demonstrate that placing thermoelectric modules on the sidewalls of the BP, in conjunction with PCM and graphite-based porous materials, significantly enhances cooling uniformity and lowers the maximum battery temperature. Their study also reveals that thermoelectric module performance is highly sensitive to applied voltage differences and ambient conditions, suggesting that fine-tuning these parameters could further improve BTMS efficiency. Luo et al. (2025) investigate this approach further by proposing a hybrid BTMS that integrates thermoelectric modules, liquid cooling, and vapour chambers to expedite the cooling process when battery temperatures rise to as high as 333.15 K. Their transient multiphysics simulation, encompassing fluid flow, heat transfer, and electric field coupling, indicates that configurations without thermoelectric modules fail to reduce temperatures below 313.15 K. In contrast, incorporating thermoelectric modules results in a significantly enhanced cooling rate of 1.905 K/min, reducing the cooling time to 630 seconds at a current of 3 A and a coolant flow rate of 0.12 m/s. The authors also demonstrate the resilience of this hybrid configuration under high discharge rates (up to 5C), meeting thermal management requirements even under extreme conditions. A more simplified hybrid arrangement is presented by Najafi et al. (2025), who examine a thermoelectric-assisted air-cooling configuration. In this experimental setup, integrating a thermoelectric module with a forced air system leads to a 17.1% increase in BP operating time, improving from 1900 s to 2300 s. The hybrid system achieves a 15.2% enhancement in heat transfer efficiency and a 14.2% increase in the Nusselt number compared to the uncooled scenario. Their study emphasises that while the thermoelectric module alone may perform poorly at higher discharge rates, the introduction of forced convection facilitates better temperature gradients across the module, significantly enhancing its thermal effectiveness. These results reaffirm that hybrid thermoelectric systems not only improve thermal uniformity and responsiveness but also optimise energy consumption, particularly when supported by environmental flow modifications.

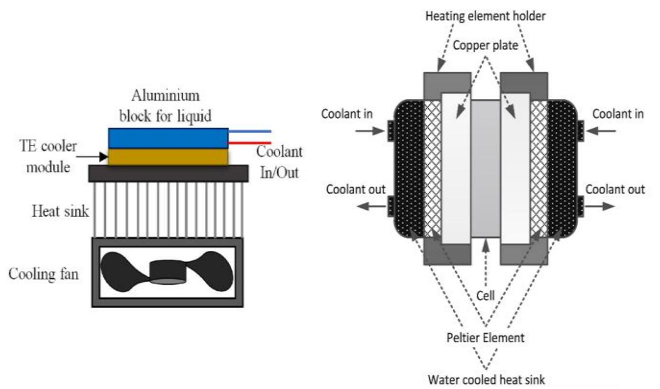

Fig. 17. Thermoelectric air-based and liquid-based cooling systems, respectively (Lyu et al., 2019; Troxler et al., 2014).

Refrigeration cooling

The method of direct refrigeration consists of a separator refrigerant and a refrigerant transfer pipe. As a consequence of eliminating the necessity for a pump, heat transfer efficiency, a more uniform distribution of temperature, basic structure, and decreased system weight are observed. In heating, ventilation, and air conditioning (HVAC) refrigerant systems, two parallel branches commonly exist: one for direct refrigerant cooling of the battery and the other for immersing the battery in refrigerant. For example, Kang et al. (2024) assess R152a and R1234yf as potential substitutes for R134a in a dual-loop cooling system. Their findings indicate that R152a enhances the coefficient of performance (COP) by approximately 19% and 10% in the air conditioning and battery direct cooling loops, respectively, whereas R1234yf results in a reduction of COP by about 23% and 22% in the same systems. Similarly, Dhamodharan et al. (2024) compare R290 and R1234yf in a two-phase refrigerant cooling configuration, reporting that R290 provides 70-113% higher heat transfer coefficients and up to 10.1% lower pressure drops compared to R1234yf. Hong et al. (2020) demonstrate that two-phase refrigerant cooling keeps battery temperatures below 45°C under challenging conditions, leading to a 16.1% increase in battery capacity and a 15.0% reduction in internal resistance compared to traditional liquid cooling methods. Guo et al. (2024) investigate an R1234yf air-conditioning system paired with a battery cooling loop, finding that R1234yf decreases HVAC cooling capacity by 8.2%–29.8% and COP by 1%-16.3% under various high-load scenarios compared to R134a. Additionally, Wu (2022) explores direct refrigerant cooling for LIBs, concluding that the system effectively maintains battery temperatures below 305 K, with negligible differences between R134a and R1234yf in terms of temperature regulation and energy consumption. As shown in Fig. 18 (Zeng et al., 2023), refrigeration cooling involves many different components, such as the compressor, raising the pressure of the coolant before going through the condenser to reject the heat taken from the battery cells via evaporators and cabin evaporators as well. The purpose of expansion valves is to adjust the pressure of the coolant before it enters the evaporators to be formed as saturated.

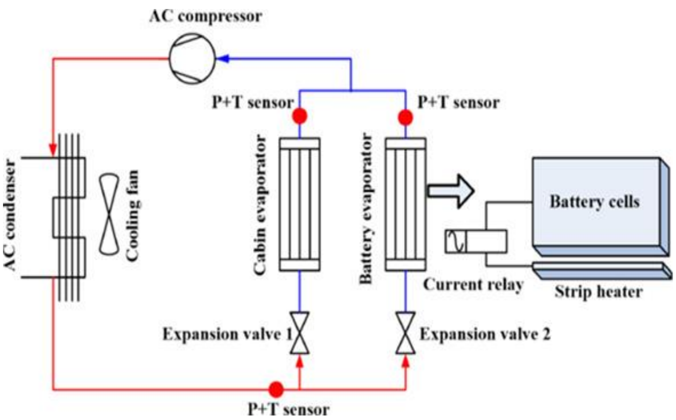

Fig. 18. A schematic of a refrigeration cooling-based BTMS system (Zeng et al., 2023).

Passive battery management systems

Battery temperature regulation does not depend on external power sources in a Passive BTMS. The mechanism of sustaining the battery temperature and releasing its heat is done by different methods such as PCMs, HPs, hydrogels, and other materials. Apart from being able to maintain a consistent temperature distribution, less power consumption due to a reduction of required power source is among the advantages of the system that leads to a decrease in operating cost. Nonetheless, the system's lack of performance hinders its applicability for high-power scenarios that utilise instant heating or cooling.

PCM based battery management systems

A phase change process that consists of absorbing or emitting heat is the principal mechanism of a PCM to store energy. This novel discovery of PCM contributes an important solution for thermal management applications by its very mechanism, which only works with latent heat (i.e. a significant amount of heat during phase change such as melting or freezing) for a certain amount of time in the absence of temperature change. Therefore, the process of charging and discharging a battery can be done with a more efficient temperature regulation. When a certain adjustment of temperature limit is exceeded, the PCM absorbs the heat as it is installed between the battery cells as can be seen in Fig. 19 (Rao and Wang, 2011) and a hit sink by changing its phase from solid to liquid. As a result, the battery temperature is sustained within the adjusted range as a significant amount of thermal energy is absorbed. Similarly, stored thermal energy is being emitted outside without encountering temperature change as the PCM transforms back its phase from liquid to solid as soon as the battery temperature drops below the previously adjusted limit. Both complex control systems and additional power requirements can be disregarded by the passive thermal management mechanism which can efficiently organise battery temperature in PCM-based BTMS. Moreover, Recent research on composite PCMs reveals substantial improvements in thermal management capabilities. For instance, Subramanian et al. (2024) find that composite PCMs based on paraffin and augmented with Al_2O_3, carbon black, and expanded graphite significantly enhance thermal conductivity and heat dissipation during 3C discharge rates. Notably, the composite featuring expanded graphite achieves superior cooling performance, reducing the maximum battery temperature by as much as 4°C when compared to natural convection methods. Their experimental validation reinforces the effectiveness of these composite PCMs in regulating battery temperatures during high-demand operations. In a separate extensive study, Hadi et al. (2025) develop a passive BTMS that combines a HP, a heat-absorbing box, and soy wax as the PCM. The use of soy wax alone leads to the absorption of 48.77% of heat energy, lowering the cell temperature by 44.57°C. When integrated into a combined system, this configuration achieves a remarkable temperature reduction of 60.16°C, corresponding to a 65.83% decrease in peak temperature. This highlights the significant advantages of employing organic PCMs alongside efficient heat transfer structures. Sutheesh et al. (2024a) also tackle the challenge of improving the thermal response times of PCMs by analysing the impact of honeycomb fin structures embedded within them. Their numerical analysis shows that both copper and aluminium fins enhance heat transfer efficiency. In particular, the use of 1-Tetradecanol and n-Eicosane results in a reduction of peak cell temperatures by up to 13.36 K, illustrating the importance of fin design and PCM selection in optimising passive cooling strategies. Mane et al. (2024) investigate a paraffin-based composite PCM infused with 1 wt% Fe_3O_4 nanoparticles, achieving a temperature decrease of 11.2°C compared to systems relying solely on natural convection. Furthermore, the addition of heat fins diminishes temperature fluctuations within the internal module from 3.1 °C to 0.9°C, leading to improved thermal consistency. Their simulations closely match experimental results, confirming the viability of these advanced composites for maintaining uniform cooling across battery systems. Additionally, Swamy et al. (2024) explore a hybrid BTMS that merges PCM with active liquid cooling, utilising nano-enhanced PCMs incorporating CuO and Al_2O_3 particles. They achieve a notable improvement in PCM melting efficiency of up to 29.33%, while optimising PCM thickness leads to a 26.98% reduction in peak temperatures. The most striking enhancement is observed in temperature uniformity, which increases by 70.79%, highlighting the benefits of hybrid thermal management approaches. In colder environments, the thermal storage properties of PCMs can be beneficial not only for cooling but also for pre-heating applications. Kim et al. (2024) investigate PCM-based thermal energy storage systems in low-temperature settings, finding that finned multitube configurations can reduce melting and freezing durations by more than 90% and 87%, respectively. The incorporation of graphene nanoparticles further boosts heat transfer efficiency, although careful consideration is required to balance energy density with material costs. Their results underscore the adaptability of PCM thermal energy storage systems in enhancing EV performance in frigid conditions. Furthermore, it is possible to engineer a PCM with adjusted working temperature bounds to meet the specifications of a certain battery. However, leakage and thermal instability can occur as a risk to complete melt of a PCM consequently in a scenario of an extremely rapid continuous charge and discharge. Additionally, consideration must be taken in PCM-based BTMS design as the melting phase change will enlarge its volume. Arduous heat dissipation caused by its relatively low thermal conductivity is another downside of the system. Reducing its convective resistance and increasing thermal conductivity can result in better performance of the thermal properties of a PCM-based BTMS as a solution to this problem. Deposition of thermally conductive fillers such as metallic foams and graphite nanoparticles, enclosure of thermally conductive plating, and instalment of fins are the three most general techniques among various others to increase the performance of organic PCMs thermal conductivity.

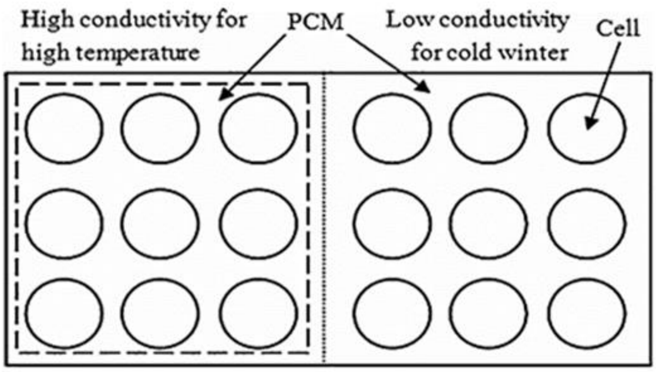

Fig. 19. PCM based thermal management (Rao and Wang, 2011).

Heat pipe cooling

The characteristics such as high heat conductivity, durability, low maintenance, robustness, cost-efficiency, and flexible design of HP-based cooling systems offer great prospective use in BTMSs designed in EVs. This cooling system offers an ideal solution for battery temperature control by utilising a small amount of working fluid flowing in passive HP devices from one position to another. Heat absorption at the evaporation module, heat release at the condensation module as well as the phase change of the inner working fluid are the operating concept of the device. Heat transfer can take place in the absence of any power requirement during which a temperature gradient exists between the two modules. The idea behind HP cooling is cooling the battery cells by a coolant passing through the pipes, which can be in liquid or gas form depending on the demand or its couple if it exists, then reject the heat to the environment via heat exchangers as illustrated in Fig. 20 (Kim et al., 2019). Recent investigations highlight considerable progress in HP-based systems, especially regarding thermal management of EV batteries. For example, Vachhani et al. (2024) present a dual evaporator loop HP designed to efficiently extract heat from multiple areas within the BP. Their innovative design effectively separates the liquid and vapour phases at the evaporator, leading to a reduction in maximum cell temperatures by as much as 22.8%, while keeping temperature fluctuations below 3.5°C, even under diverse charge and discharge scenarios. This system significantly enhances heat dissipation throughout the battery, thereby improving thermal stability and discharge performance, particularly in high-temperature environments. In a similar vein, Hendrayanto et al. (2024) examine a flat loop HP that incorporates dual heat sources, replicating standard EV battery configurations. Their research demonstrates the system's ability to manage heat loads between 20 and 100 W, achieving a thermal resistance of 0.17°C/W. This dual-source arrangement reduces surface temperature differentials and shows promise for maintaining battery temperatures below critical limits, thus reducing the risk of thermal runaway, which is vital for the safe operation of EVs. The choice of working fluids plays a crucial role in optimising passive cooling systems as well. Kumar and Goel (2024) investigate oscillating HPs filled with various fluids, including acetone, methanol, and ethanol. Their findings indicate that an oscillating HP filled with acetone at a 70% filling ratio demonstrates exceptional performance, lowering the average cell temperature by 17% and decreasing maximum temperature variations by 65%. These results highlight the significance of fluid characteristics and filling ratios in enhancing the cooling efficiency of passive systems under high discharge rates. Additionally, Gabsi et al. (2024) explore the application of nanofluids in loop HPs to further advance thermal management capabilities. Their analysis reveals that CuO-water and Al_2O_3-water nanofluids significantly improve heat transfer compared to traditional water-filled loop HPs. Specifically, CuO-based mixtures yield superior thermal performance, with an optimal nanoparticle concentration of 6-8% providing the best results; beyond this range, thermal resistance increases. This study emphasises the critical influence of nanofluid type and concentration in developing more effective loop HP systems for EV batteries. Finally, Yang et al. (2024b) propose a flat confined loop HP design to mitigate the problem of uneven temperature distribution across the battery surface. Their numerical simulations demonstrate that the flat confined loop HP enhances temperature uniformity and boosts heat dissipation, particularly in spatially constrained battery configurations. This design presents a promising strategy for addressing localised hotspots and ensuring safe battery operation in more compact EV designs.

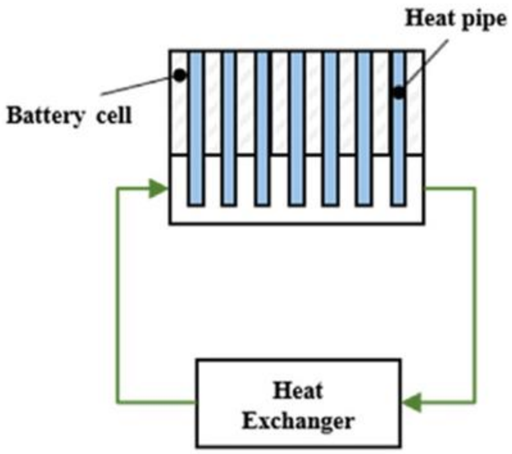

Fig. 20. HP cooling schematic (Kim et al., 2019).

Regardless of the high thermal conductivity, heat dissipation at the conduction section is often escalated with the utilisation of forced working fluid, such as air or liquid, installed in the HPs. Liquid or air-cooling systems are reported to be used by nearly all various cooling systems integrated inside a BTMS in a study review on the use of HP technology in BTMS and a list of EVs among the UK/European markets. All things considered, Table 5 (Ali, 2023) is represented, comparing the different BTMS techniques with respect to the various parameters explained.

Table 5. Different BTMSs with several properties (Ali, 2023).

Cooling Method	*Power constraint*	*Heat transfer rate*	*Fluid thermal conductivity (W/mK)*	*Thermal management type*	*Construction*	*Space requirement*	*Cost*	*Temperature uniformity*
Air Cooled	Yes	Low	0.0242	Heating/cooling	Simple	High	Cheap	Ineffective
PCM	No	High	16.6	Cooling only	Simple	Flexible	Cheap	Effective
HP	No	High	8.6	Heating/cooling	Complex	Flexible	Cheap in long run	Effective
Liquid cooled	Yes	High	0.3892	Heating/cooling	Complex	High	Expensive	Effective

Hybrid battery management systems

Coupling system

In some cases, it has been observed that a single BTMS strategy is not sufficient to achieve the desired threshold temperature for optimal performance of LIBs. As a result, researchers and manufacturers have started using a combination of two or three systems to ensure optimal thermal performance and safety for EVs, whilst also declining the risk of thermal runaway and other hazardous conditions. A hybrid thermal management system for batteries combines both passive and active BTMS methods, making it highly effective and practical for extreme working conditions (Paneerselvam et al., 2024). This system offers the advantages of both methods, including affordability, adaptability, and effectiveness, and can greatly improve thermal management performance and safety for LIBs in EVs. The use of hybridisation (Amer et al., 2024) allows for the optimisation of thermal management objectives while minimising energy and power consumption, cost, volume, and weight of BTMSs. Additionally, thermal runaways can be prevented by hybrid BTMS and enhancement in efficiency and service life of LIBs in cold weather conditions can be achievable. Overall, the application of hybrid BTMS offers various benefits, including enhanced thermal management, safety, efficiency, and service life of LIBs. Currently, most coupled thermal management systems take advantage of PCMs and other types of coupling (Wang et al., 2022), such as air coupled with PCM, air and other types of coupling, liquid and PCM coupling, HP and PCM coupling, HP and other ways of coupling, and PCM coupled with any.

Liquid with air cooling

The hybrid cooling strategy integrates liquid and air-cooling techniques for optimal thermal management (The International Journal of Heat and Mass Transfer, 1960). The primary cooling mechanism employed is liquid cooling; it is a nonelectrically conductive fluid, including hydrofluoroether, to spray over the battery cells and absorb the excess heat through evaporation. It involves the circulation of a coolant close to the battery cells (Zhao et al., 2023a). Air cooling uses a fan or a blower to force air through the gaps between the battery cells and remove the heat by convection. However, when the cooling requirements surpass the capabilities of the liquid cooling system, air cooling serves as an auxiliary method to eliminate excess heat (Zhao et al., 2021a). This process involves directing air over the surfaces cooled by the liquid or through exhaust vents to enhance the cooling effect (Rallabandi and Selvaraj, 2024). By integrating these two cooling methods, the hybrid approach effectively strikes a balance between thermal performance and the longevity and safety of battery cells. Al Tahhan et al. (2024) present an innovative hybrid BTMS that combines air and liquid cooling to optimise temperature regulation in small-scale EV applications. Experimental results obtained in a climate chamber indicate a significant enhancement in cooling efficiency and temperature uniformity by 21.04%. This system demonstrates robustness under varying operational stresses, suggesting its potential for application in larger battery systems. Zhang et al. (2024) similarly propose a hybrid cooling solution that merges air and liquid cooling techniques to mitigate condensation risks in LIBTMS operating in high-humidity conditions. Their CFD simulations optimise the system design, achieving a 39.68% reduction in condensation. The incorporation of a return air structure and flow deflectors further improves the prevention of condensation, making this hybrid system a dependable option for high-humidity environments, particularly in EVs. In another study, Zhao et al. (2023b) develop a hybrid BTMS that combines direct liquid cooling with forced air cooling for cylindrical LIB modules. Their numerical simulations reveal optimal configurations, such as maintaining a 5-mm gap between the battery and the liquid-cooling jacket, which enhances heat dissipation and cooling efficiency, especially during high-rate operational scenarios. Importantly, the direct liquid cooling component also provides fire suppression capabilities, thereby improving the safety of EVs. Likewise, Xin et al. (2023) introduce a hybrid BTMS that integrates air cooling and liquid cooling through heat conducting blocks to manage effective heat transfer. Their simulations demonstrate that the optimal design achieves a balance between cooling efficiency, power consumption, and overall system weight. The findings indicate that air cooling significantly enhances temperature uniformity, leading to a reduction in the maximum temperature difference. This hybrid configuration is especially effective in maintaining safe operating temperatures for BPs, particularly when using intermittent air cooling. The collective insights from these studies highlight that hybrid cooling strategies, which integrate both air and liquid cooling methods, are highly effective in improving thermal management, enhancing safety, and ensuring optimal performance of LIBs across various applications, including EVs.

PCM integrated air cooling battery management systems

As the name suggests, this cooling system couples active air-cooling methods with the use of PCMs. It has been previously stated that the main disadvantage of using PCMs is that once they melt and the phase is changed, a loss in their ability can be observed to regulate the temperature of the battery effectively. Therefore, incorporating as well as considering active cooling methods is required. By taking forced air circulation into account properly, an improvement in the cooling reliability and performance of the PCM can be achieved, which results in a more uniform temperature distribution for the batteries (Gharehghani et al., 2024). In 2014, Fathabadi (2014) introduced the concept of a synergistic cooling strategy that combines air and PCM for BTM. This approach involves using airflow through thin ducts as the active component, whilst the PCM with a desirable latent heat serves as the passive component. The results of their study demonstrated that this hybrid BTMS, which combines PCM with air cooling, was able to effectively regulate the temperature of a BP within the recommended range, even at an ambient temperature of 55°C. Additional research continues to investigate hybrid BTMS that merge air cooling with PCMs, resulting in notable enhancements. He et al. (2025) introduce an innovative hybrid BTMS featuring a semi-elliptical PCM arrangement, which achieves an 18.3% reduction in maximum temperature compared to systems relying solely on air cooling. The temperature difference is reduced by 49.9%, underscoring the significant advantages of integrating both active and passive cooling techniques. When compared to other PCM configurations, this arrangement demonstrates considerable superiority, particularly under fluctuating discharge rates. In a related study, Zhou et al. (2024) propose a hybrid BTMS that combines air jet impingement cooling with internal PCM. Their findings reveal a 44.9% decrease in maximum temperature relative to PCM-only systems, alongside improved temperature uniformity with a 19.7% reduction in temperature differential when compared to air jet impingement-only systems. Optimising the nozzle layout further enhances the temperature difference by 49.7%, highlighting the effectiveness of this combined cooling strategy. Moreover, Sajedi and Molaeimanesh (2024) present a hybrid BTMS that employs refrigerated air cooling alongside PCM. Their results indicate that incorporating fin structures, particularly spiral designs, leads to an average temperature reduction of 4.2°C within the module. Their research also indicates a decrease in energy consumption by approximately one-third, providing long-term operational advantages compared to traditional active cooling systems. This blend of cooling techniques is effective for preserving battery health while minimising energy consumption, reinforcing the benefits of hybrid approaches. Lastly, Song et al. (2024) showcase a dual-layer PCM configuration integrated with air cooling, resulting in a 21.5% reduction in maximum temperature under high ambient temperatures and discharge conditions. This system ensures improved temperature regulation and uniformity, making it a promising solution for effective BTMSs faced with demanding operational environments. Suo et al. (2024) investigate the thermal efficiency of a BP using a combined approach of PCM and air cooling. Their study introduces four distinct PCM configurations to assess heat dissipation performance and optimise PCM proportions, aiming to achieve better temperature uniformity, reduce energy loss, and minimise PCM volume. Their findings demonstrate that thermal performance with PCM outperforms that of systems without PCM, with Case 4, utilising a specific PCM arrangement, not only enhancing thermal performance but also decreasing PCM volume by 43.06%, leading to substantial material savings. These results emphasise the growing significance of hybrid BTMS that incorporate both passive and active cooling methods. The integration of PCMs with air cooling, as illustrated by various studies, proves to be a successful strategy for attaining more uniform temperature distributions, enhancing overall performance, and prolonging battery life in EVs and energy storage systems.

PCM with liquid cooling battery management systems

A hybrid BTMS strategy that involves both liquid and PCM has become a popular way of battery cooling technology in recent years. The liquid cooling system is a widely used technique for keeping the temperature in optimal range in EVs. In spite of the fact that the heat dissipation rate in liquid cooling is greater compared to air cooling, it may still be insufficient in some cases (Liu et al., 2022a). For instance, there is often not enough compatibility between the coolant tube and the cylindrical shape of the battery, which consequences in a poor contact surface area. In addition to that point, the risk of leakage and deranged temperature distribution pose significant challenges for the application of liquid cooling-based BTMS. In order to overcome these limitations, an integration of PCM with a liquid system is a valid and applicable solution for improved thermal management. In this approach, PCMs behave as a thermal buffer, absorbing and storing overheat during periods of high demand (Rallabandi and Selvaraj, 2024). The liquid cooling system then circulates the coolant through heat exchangers embedded with PCMs, facilitating the dissipation of the stored heat (Mustafa et al., 2022). This hybrid method helps regulate temperature variations and enhances the overall efficiency of the cooling process (Maity, 2015). Existing studies on liquid-PCM hybrid BTMS have focused on its impact on improving the thermal performance of BPs, parametric optimisation, structure design, cooling strategy adjustment, large-scale application, and thermal runaway prevention. For example, Chen et al. (2025) create a hybrid BTMS that integrates tubular composite PCMs into wave-shaped cooling plates. Their 3D numerical modelling reveals that cross-flow circulation significantly enhances temperature uniformity. The optimal configuration, which includes 9% expanded graphite-doped PCM, a flow velocity of 0.05 m/s, and a PCM layer thickness of 2.5 mm, results in a 22.2% reduction in peak temperature while considerably decreasing temperature gradients throughout the BP. In a similar study, An et al. (2025) design a lightweight hybrid system that combines mesh-like coolant channels with subdivided PCM chambers made through 3D printing. This configuration effectively limits the maximum cell temperature to 43.83°C during 3C discharge, yielding a 20.13°C improvement compared to traditional aluminium cold plates. The system maintains consistent thermal performance across various flow rates and inlet-outlet arrangements. In a more comprehensive review, Jhariya et al. (2024) highlight that hybrid systems utilising nano-enhanced composite PCMs can achieve a temperature reduction of up to 50% in batteries compared to standard configurations. They also emphasise the need to tackle practical issues such as system complexity, increased weight, and scalability. To address PCM saturation challenges under extreme conditions, Luo et al. (2024) propose a hybrid design that combines liquid channels with snowflake-shaped fins. This innovative structure successfully maintains a temperature difference of less than 3°C at 3C discharge rates and demonstrates excellent thermal control even at 5C and 40°C ambient temperatures. Their findings underscore the significance of fin geometry and flow optimisation in delaying thermal saturation effectively.

Thermoelectric with liquid cooling

This technique is a hybrid cooling system that combines the benefits of both TCS and liquid cooling to maintain the optimal temperature and performance of the BP. It operates based on the Peltier effect (Pakrouh et al., 2023), using a thermoelectric device (TED) consisting of two dissimilar materials connected by an electric circuit. When an electric current flows through the circuit, one material becomes hot and the other becomes cold, creating a temperature difference. The cold side of the TED is attached to the BP, while the hot side is connected to a heat sink that is cooled by a liquid, such as water or glycol. This process actively removes heat from the battery cells, absorbing it on one side and releasing it on the other (Panchal et al., 2016). Liquid cooling is also utilised to enhance this heat dissipation process by facilitating heat transfer from the TEDs to a coolant, which can then be circulated and cooled externally. Recent experimental findings by Panmuang et al. (2024) demonstrate that this hybrid approach, particularly with a water flow rate of 4.0 l/min, can reduce battery temperatures by up to 52%, significantly outperforming standalone air or liquid cooling systems. Furthermore, lower flow rates such as 1.0 and 2.0 l/min also effectively manage thermal loads with reduced energy consumption, extending battery lifespan through improved temperature stability. However, existing studies are limited in addressing the potential challenges and risks associated with TE liquid cooling systems (Rallabandi and Selvaraj, 2024).

Nanofluid with air cooling

A hybrid cooling solution, which combines nanofluid cooling and air-cooling techniques, offers a promising solution for efficient heat dissipation (Yu et al., 2012). Nanofluids, which are coolant fluids interspersed with nanoparticles, have been shown to significantly enhance heat transfer capabilities. By incorporating nanofluids into liquid cooling systems and using air cooling as an auxiliary method, excess heat can be effectively removed from the surfaces being cooled (Nandan, 2019). In recent years, the impact of temperature on the safety, performance, and lifespan of LIBs has been widely acknowledged. Soleymani et al. (2023) find that replacing an air-cooled system with a liquid cooling system incorporating nanoparticles give rise to temperature reductions of 7.89% and 4.73% for Al_2O_3 and CuO, respectively. Rani et al. (2017) highlight that liquid cooling, particularly with Al_2O_3 nanofluid, can effectively maintain battery temperatures within safe limits, enhancing overall system efficiency and ensuring safe operation. However, further research is needed to optimise the composition of nanofluids for maximum cooling efficiency and to ensure their long-term stability and potential consequences when used in air cooling systems.

HP - PCM cooling

High discharge rate or cycling circumstances due to a failure caused by fatigue in phase-transition enthalpy are more vulnerable to exist in PCM based BTMS as a result of poor thermal properties of PCM. Lately, further techniques of practical assistance in the heat dissipation of PCM benefit from HP utilisation. Not only the significant latent heat capacity of PCM is considered in this integration, but also the high thermal-transfer outcome of HPs. This integrated system generally transfers the heat absorbed by PCM from the evaporation module to the condensation module and then releases the heat into a reservoir (i.e. the environment) employing liquid cooling or air convection (Liu et al., 2022a). Recent research highlights the effectiveness of hybrid HP and PCM systems across various setups and operational conditions. Sharifi et al. (2025) introduce a simplified passive cooling approach that avoids direct contact between the PCM and the battery surface. Their findings indicate that integrating PCM can lower battery temperatures by as much as 14%, particularly at lower air velocities, with their numerical model showing strong alignment with experimental data. Gao et al. (2024) further illustrate the advantages of combining PCM with HP systems compared to those using only PCM, demonstrating a temperature reduction of 34.9% at a 4C discharge rate. They also observe a notable decrease in internal temperature variation, dropping from 9.76°C to 1.99°C, which signifies enhanced thermal uniformity, even under rigorous cycling conditions. Likewise, Li et al. (2025) explore a passive BTMS that incorporates U-shaped HPs and PCM, taking advantage of ambient airflow during dynamic driving. Their design effectively maintains safe operational temperatures with minimal gradients, without requiring any additional energy input. Sutheesh et al. (2024b) improve PCM conductivity by incorporating nanoparticles, termed nano boosted PCM and find that both the concentration of these particles and the orientation of the battery cells considerably affect thermal performance. A horizontal arrangement of cells, for instance, resulted in a 1.52 K decrease in average temperature, while higher air velocity in the condenser region shortened overheating durations, emphasising the importance of efficient heat rejection. Bian et al. (2024) investigate real-life driving conditions and discover that the combination of HP and PCM surpasses standalone systems in managing peak temperatures and maintaining uniformity. When driving at 120 km/h, their system achieved a 13.9% reduction in temperature rise, with the HP mainly responsible for controlling peak temperatures and the PCM ensuring an even distribution. Their results highlight the significance of thermal gradients and environmental conditions, as the PCM effectively delays temperature increases during uphill driving scenarios. However, the study also pointed out that in extreme situations, such as thermal runaway, the system may lack responsiveness, which necessitates supplementary emergency thermal management solutions. In addition, He et al. (2024) try to improve a numerical model for arrays of micro HPs integrated with PCMs. Their results observe that under forced convection conditions of 50 W/(m^2 K), the system successes a maximum temperature reduction of 29.9% during short-circuit scenarios, representing a considerable improvement over traditional air-cooled systems. Nevertheless, the study also raises potential challenges, such as the increased mass associated with PCM incorporation and limitations in performance related to heat rejection on the condenser side, which must be considered in practical applications. Furthermore, a table below presents time-dependent temperature values obtained from an experimental study (Yamada et al., 2017). Collectively, these investigations reinforce the importance of integrating HP and PCM within advanced BTMSs, delivering dual benefits of enhanced thermal conductivity and phase change enthalpy while maintaining simplicity in structure and energy efficiency across both experimental and numerical evaluations.

Table 6. Time-dependent temperature values in °C with different configurations of HP and PCM BTMS methods (Yamada et al., 2017).

Time (s)	*No Device*	*PCM*	*HP*	*HP+PCM*
0	25.7	26.5	26.2	25.8
60	58.9	50.5	51.4	44.3
120	88.2	65.4	66.2	53.4
240	131.4	91.2	82.9	60.7
300	143.9	100.6	88.8	63.9
480	-	115.6	102.9	72.5
720	-	123.7	116.1	80.3
900	-	124.8	123.2	85.5
1500	-	141.5	135.4	96.1
2700	-	-	143.7	111.2
3600	-	-	147.2	118.8

Overall, Table 7 provides a comprehensive comparison of various battery cooling methods employed in BTMSs. Each method is evaluated based on six critical parameters: cooling mechanism, heat transfer efficiency, energy consumption, system complexity, thermal uniformity, and cost. The table includes conventional, advanced, and hybrid cooling strategies, allowing for a broader understanding of their operational characteristics and applicability. Traditional methods, such as air and liquid cooling, are presented alongside more advanced technologies like nanofluids, HPs, and thermoelectric cooling. Additionally, hybrid systems are thoroughly assessed, highlighting the synergistic benefits achieved through combining multiple mechanisms like PCM with HPs, thermoelectric modules with liquid cooling, or nanofluids with airflow. The findings indicate that while advanced and hybrid methods generally offer superior thermal uniformity and heat transfer efficiency, they tend to involve higher energy consumption, system complexity, and costs. Conversely, simpler methods, although cost-effective, may not meet the thermal requirements of high-performance battery systems. This comparative table serves as a valuable tool for identifying suitable cooling approaches tailored to specific thermal performance targets and operational constraints within EVs or energy storage applications.

Table 7. In-depth analysis of BTMS cooling methods (Gharehghani et al., 2022; Abdelkareem et al., 2022).

Method	*Cooling mechanism*	*Heat transfer efficiency*	*Energy consumption*	*System complexity*	*Thermal uniformity*	*Cost*
Air cooling	Convection-based airflow across battery surfaces	★★	★	★	★★	★
Liquid cooling	Circulating coolant through channels or cold plates	★★★★★	★★★	★★★★	★★★★	★★★★
HPs	Passive phase-change heat transfer via evaporation/condensation	★★★★	-	★★★	★★★★★	★★★
PCM	Latent heat absorption through the melting phase	★★★	-	★★	★★★	★★★
Thermoelectric cooling	Active heat pumping via Peltier effect	★★★	★★★★★	★★★★	★★★★★	★★★★★
Refrigeration cooling	Vapour compression or absorption cycles to extract heat	★★★★★★	★★★★★★	★★★★★★	★★★★★	★★★★★★
PCM + Air	PCM absorbs peaks + air removes stored heat	★★★★	★★★	★★★	★★★★	★★★
PCM + Liquid	PCM buffers peaks + liquid maintains stability	★★★★★	★★★★	★★★★★	★★★★★	★★★★★
Thermoelectric + Liquid	Active thermoelectric heat pumping supported by coolant circulation	★★★★★	★★★★★★	★★★★★★	★★★★★	★★★★★★
Nanofluid + air	Air removes heat while nanofluid enhances specific zones	★★★★★	★★★	★★★★★	★★★★	★★★★★
HPs + PCM	HPs transfer heat stored in PCM	★★★★★	-	★★★	★★★★★	★★★

Low: ★ , Low to medium: ★★ , Medium: ★★★ , Medium to high: ★★★★ , High: ★★★★★ , Very high: ★★★★★★

CONCLUSION

This study provides a comprehensive exploration of EVs and their primary power source, LIBs. Throughout the paper, several key areas have been examined, including the development of EV technologies, the importance of LIB thermal management, the lifecycle and performance challenges of batteries, and the various methods of battery recycling. By emphasising the environmental benefits of EVs and the critical role they play in reducing carbon emissions, the study underscores the importance of overcoming the technical challenges that still exist, particularly in relation to battery performance and thermal safety.

A significant portion of the study focuses on the thermal management of LIBs, recognising its vital role in ensuring both the longevity and safety of the batteries. Different cooling systems, such as air cooling, liquid cooling, PCM based cooling, and thermoelectric systems, are evaluated in terms of their effectiveness and limitations. Additionally, the disposal and recycling of spent LIBs is a crucial concern. The paper explores the various recycling techniques available, such as pyrometallurgy, hydrometallurgy, and direct recycling, and their effectiveness in recovering valuable materials whilst minimising environmental impact as well. With the growing demand for EVs, the importance of establishing an efficient recycling infrastructure is highlighted, as it will be critical to maintaining the sustainability of these technologies. In summary, the bullet point below indicates the most critical points about the comprehensive study examined from this broad perspective.

- EVs are essential for reducing reliance on fossil fuels and achieving environmental sustainability. They play a pivotal role in curbing GHG emissions and addressing climate change.
- LIBs stand out as the most suitable power source for EVs, owing to their high energy density, long lifespan, and ability to provide sufficient range for modern transportation needs.
- Thermal management is critical for the safe and efficient operation of LIBs. The study explores various cooling systems, identifying both their strengths and limitations. Proper thermal regulation is essential to avoid issues such as thermal runaway, which can lead to dangerous battery malfunctions.
- Recycling of spent batteries is becoming increasingly important as the number of EVs on the road continues to rise. Recycling methods like pyrometallurgy and hydrometallurgy have proven effective, but there is also great potential in the further development of direct recycling technologies.
- Sustainability concerns extend beyond just the use phase of batteries. The environmental impacts of battery production and disposal must be carefully managed, particularly as demand for LIBs grows.

Looking ahead, several areas warrant further exploration to ensure that EV and battery technologies continue to evolve sustainably:

- Further study is needed to explore advanced cooling technologies that can better regulate battery temperatures, particularly in high-stress operating environments. This will help extend battery life and improve safety.
- Even though current recycling processes are effective, new methods need to be developed that are both more cost-efficient and capable of recovering a higher percentage of valuable materials. Direct recycling, in particular, holds promise but requires more focused research to overcome existing technological challenges.

- The production of LIBs involves energy-intensive procedures. There is a pressing need for cleaner, more sustainable production methods that reduce the environmental footprint of battery manufacturing. In addition, the concept of second-life applications for LIBs, where batteries are repurposed for stationary energy storage systems after their use in EVs, should be further explored to maximise their lifecycle.

Looking towards the future, battery technologies are expected to evolve rapidly to meet the increasing demands of electric mobility and grid-level energy storage. One of the most anticipated breakthroughs lies in the development of solid-state batteries, which aim to deliver higher energy densities, faster charging capabilities, and improved safety due to the elimination of flammable liquid electrolytes. These next-generation systems, although currently in the prototype or pilot production stages, are projected to significantly outperform conventional lithium-ion chemistries once their scalability and cost-effectiveness are improved. Furthermore, advanced battery management systems powered by artificial intelligence are poised to enhance operational efficiency and extend battery life through predictive analytics and real-time optimisation. The integration of sustainable materials, including cobalt-free and silicon-based electrodes, also reflects a growing research interest in reducing environmental and ethical concerns associated with current supply chains. As electrification expands into sectors beyond transportation, such as aviation and marine applications, it is essential that research continues to focus on developing adaptable, high-performance, and circular battery technologies that align with global decarbonisation targets. These advances will play a vital role in shaping the sustainable energy systems of tomorrow. In conclusion, whilst EVs and LIBs have made remarkable strides in declining the environmental impact of transportation, continued advancements in battery performance, recycling, and sustainability are essential to ensuring that these technologies can meet future demands in an environmentally responsible manner.

RECOMMENDATIONS

LIB technology is widely favoured across various applications such as EVs, energy storage systems, and portable electronic devices due to its high energy density, long cycle life, and excellent efficiency. However, there are significant technical, environmental, and cost-related differences between the various chemical compositions used in LIBs (such as NMC, LFP, NCA, LTO, etc.). Hence, selecting the most suitable battery type according to users' needs, operating conditions, and environmental awareness is of great importance.

To begin with, for users primarily engaging in urban driving, LFP batteries may represent an ideal choice. Owing to their high thermal stability, safety, and long cycle life, LFP batteries are highly effective for regular, short- to medium-distance travel. They can retain up to 80% of their capacity for around 2,000-4,000 cycles and operate at an efficiency of 92–98%, making them economically attractive. However, their energy density is lower than that of NMC or NCA batteries (typically 90–190 Wh/kg), which means they take up more space, potentially posing installation challenges in compact vehicles. That said, their superior tolerance to high temperatures reduces the need for extensive thermal management in hot climates, including in the Mediterranean or the Middle East.

For long-distance drivers or users of high-performance EVs, NCA batteries offer a powerful alternative. With a notably high energy density (200–322 Wh/kg), they are particularly well-suited for applications requiring extended range. Favoured by brands like Tesla, NCA batteries provide greater range with less weight. However, their high energy density also introduces heightened thermal management requirements and safety risks, making advanced BMS essential. Additionally, their cycle life is generally shorter than that of LFP batteries, and they tend to experience faster capacity degradation under irregular usage patterns.

In cold climate regions, such as Northern Europe or Canada, LTO batteries are a viable option. These batteries can operate in temperatures as low as -30°C and are known for their exceptional thermal stability. They also offer an impressive lifespan of 5,000 to 10,000 cycles. Nonetheless, their energy density is quite low (typically 50–90 Wh/kg), making them more suitable for use in applications where range is less critical, such as public transport (e.g. electric buses) or stationary energy storage systems.

For users requiring a balanced performance profile and rapid charging capabilities, NMC batteries present a versatile solution. With an energy density ranging from 150–220 Wh/kg, they support fast charging and can withstand high discharge currents. Compared to LCO, NMC is safer; compared to LFP, it offers higher energy density; and compared to NCA, it tends to be more cost-effective. However, to maintain optimal performance and lifespan, the proportions of nickel, manganese, and cobalt must be properly balanced. Imbalances can result in reduced cycle life.

From an environmental sustainability perspective, LFP batteries stand out as one of the most eco-friendly options. As they do not contain cobalt, they have a lower toxic chemical profile and a higher recyclability rate. In contrast, NMC and NCA batteries, due to their cobalt and nickel content, pose greater environmental burdens during production and may also raise ethical concerns regarding labour practices in mining (e.g. child labour in cobalt extraction). LTO batteries are also considered environmentally friendly, though the use of titanium increases manufacturing costs. Overall, LFP batteries are advantageous in terms of cost, environmental impact, and cycle life, aligning well with low carbon footprint goals.

Consequently, depending on the user profile, LFP batteries are most suitable for urban driving at low speeds with frequent charging opportunities or for use in hot climates where safety and environmental concerns are prioritised; NCA batteries are ideal for long-distance travel, fast charging, and high-performance needs; NMC batteries offer a balanced option in terms of performance, cost-effectiveness, and medium range; and LTO batteries are best suited for extremely cold climates where ultra-long cycle life is essential, and limited range is acceptable.

Additionally, when purchasing a vehicle, factors such as the quality of the BMS, the manufacturer's experience in battery cell production, warranty coverage, and service network infrastructure should also be considered. Users are advised to avoid full discharges, keep charge levels between 20–80% whenever possible, and not to leave the vehicle in extremely hot or cold environments for extended periods. Looking ahead, solid-state batteries are anticipated to be the natural evolution of LIBs, offering safer and more compact solutions. However, this technology is still in the developmental stage. For now, LFP batteries should be favoured for their sustainability and safety, whilst NCA and NMC are better suited for performance and range-focused applications.

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