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Original Research Article

A review and case study about the impact of temperature and ageing on electric vehicle batteries

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ABSTRACT

Battery aging is a critical factor affecting the performance, reliability, and lifespan of electric vehicles (EVs). Among the various factors influencing battery degradation, temperature plays a decisive role. High temperatures accelerate chemical reactions within lithium-ion cells, leading to capacity loss and increased internal resistance over time. This degradation reduces the battery's overall energy storage capacity and efficiency. Conversely, exposure to low temperatures impairs battery performance by slowing down electrochemical reactions, reducing available capacity, and increasing resistance during discharge. Effective thermal management systems are essential to mitigate these effects, ensuring stable operating conditions and prolonging battery life. Understanding the relationship between temperature and battery aging is vital for optimizing battery performance, improving EV range, and developing strategies to extend battery life while maintaining safety and efficiency. In this article, the most important aspects about battery ageing and effects of environment temperatures on batteries and EV range are presented with most recent case studies.

Keywords: EV batteries; battery life; temperature; EV; range

1. Introduction

The rise of electric vehicles (EVs) represents a pivotal shift towards sustainable transportation. Central to the performance and longevity of EVs are their batteries, which are highly susceptible to temperature fluctuations. Understanding the intricate relationship between temperature and EV batteries is crucial for optimizing their performance and ensuring their long-term viability. This essay explores the influence of temperature on EV batteries, drawing insights from state-of-the-art research findings to reveal the underlying mechanisms and implications.

A battery system's selection and size depend on the vehicle's requirements. A hybrid vehicle can refer to a wide variety of vehicle concepts. Here are a few classifications of vehicle concepts. The classifications of different car manufacturers are remarkably similar. Overviews have been given by [2, 4]. Fig. 1 provides a comparison of various types of electrified vehicles in terms of energy and power demand. Although fuel-cell electric vehicles are not explicitly discussed, their battery sizing and requirements are generally comparable to those of full hybrid electric vehicles illustrated in Fig. 1.

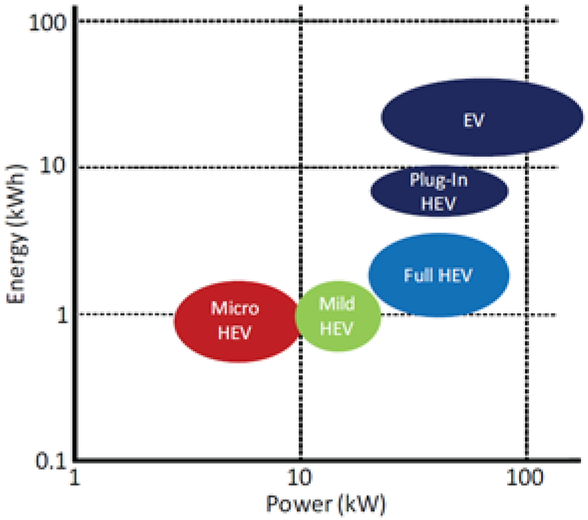

Fig. 1. Battery energy and power demands for various types of electrified vehicles (based on market observations, [6]). EV: electric vehicle; HEV: hybrid electric vehicle.

1.1. Lithium-ion battery

According to [6] the term "lithium-ion batteries" encompasses a wide range of material combinations used to construct these batteries. The characteristics of lithium-ion batteries, including power, lifespan, performance at low and high temperatures, and safety, are highly dependent on the specific materials used. The electrode design allows optimization towards high-power or high-energy cells. According to Fig. 2, lithium-ion battery cells achieve the highest gravimetric energy and power densities of all commercially available rechargeable batteries. Using titanate instead of carbon for the negative active material can achieve very long lifetimes and high safety levels. However, this choice significantly reduces energy density, [7].

A lithium-ion battery (often called Li-ion battery or LIB) is a type of rechargeable battery that uses the reversible intercalation of Li^+ ions into electronically conducting solids to store energy. Compared to other commercial rechargeable batteries, Li-ion batteries are characterized by [8]:

- *Higher specific energy*
- *Higher energy density*
- *Higher energy efficiency*
- *Longer cycle life*
- *Longer calendar life*

Significant advancements have occurred in lithium-ion battery properties since their mass production for Sony camcorders in 1991. Within the next 30 years, their volumetric energy density increased threefold while their cost dropped tenfold, [9]. These batteries have enabled portable consumer electronics, laptops, cellular phones, and electric cars, contributing to what is known as the e-mobility revolution. They are also widely used for grid-scale energy storage, military applications, and aerospace. Different chemistries of Li-ion batteries exist, including lithium cobalt oxide ($LiCoO_2$), lithium iron phosphate ($LiFePO_4$), lithium manganese oxide ($LiMn_2O_4$ spinel or LMR-NMC), and lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$ or NMC). Each chemistry offers specific advantages and trade-offs, [10]. The invention and commercialization of Li-ion batteries have had a profound impact on technology and society, recognized by the 2019 Nobel Prize in Chemistry, [10]. These batteries continue to play a crucial role in our daily lives and the transition toward cleaner energy sources, [11].

1.2. Design and electrochemistry

Lithium-ion batteries are widely used in various devices, including mobile phones, laptops, and electric vehicles. Following sections describe how they work.

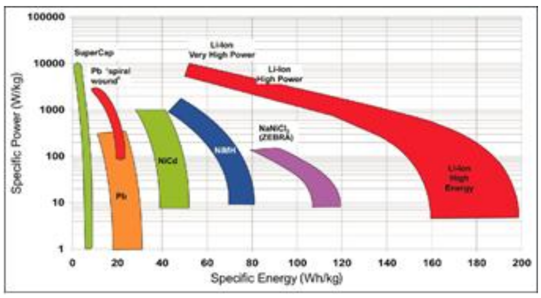

Fig. 2. Ragone plot of various battery technologies with specification at cell level for automotive applications without lithium sulphur and metal-air batteries, [6]. SuperCap: supercapacitor; Pb: lead; Li-ion: lithium-ion; NiCd: nickel-cadmium; NiMH: nickel-metal hydride; $NaNiCl_2$: sodium-nickel chloride; ZEBRA: Zero Emission Battery Research Activities.

1.2.1. Battery components

A lithium-ion battery consists of several

individual cells connected to each other. Each cell contains three main parts, [12] [13]:
Positive Electrode (Cathode): This electrode is typically made of lithium-metal oxide, such as lithium-cobalt oxide ($LiCoO_2$). It supplies lithium ions (Li^+).
Negative Electrode (Anode): The anode usually contains a lithium-carbon compound, allowing for easy movement of lithium ions in and out of its structure.
Liquid Electrolyte: The electrolyte facilitates the movement of lithium ions between the electrodes.
Additionally, there are components known as "current collectors," which are conductive foils situated at each electrode of the battery, linking them to the cell terminals. These terminals facilitate the flow of electric current between the battery, the device, and the energy source powering the battery. Lastly, the "separator" is a porous polymeric film that divides the electrodes while facilitating the transfer of lithium ions from one side to the other, [10], [14]. These parts are illustrated in the Fig. 3.

1.2.2. Electrochemistry

Inside the battery, oxidation-reduction (Redox) reactions occur. Reduction takes place at the cathode (positive electrode).
Cobalt oxide (C_0O_2) combines with lithium ions (Li^+) to form lithium-cobalt oxide (LiC_0O_2). Oxidation occurs at the anode (negative electrode). The graphite intercalation compound LiC_6 forms graphite (C_6) and releases lithium ions.

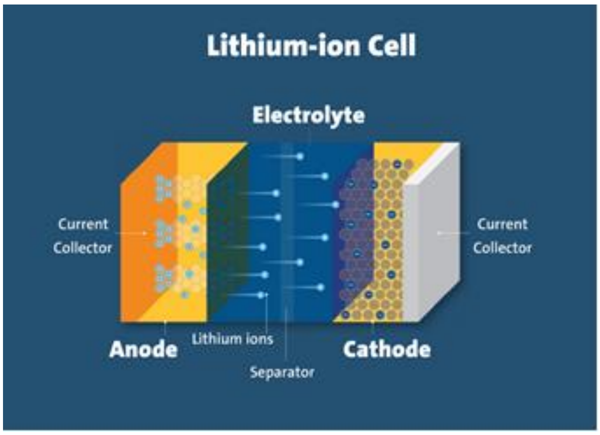

Fig. 3. Components of a lithium-ion battery cell, [5].

During the recharging process positively charged lithium ions (Li^+) move from the negative anode to the positive cathode through the electrolyte. The electrical current flows from the current collector through the device being powered (e.g., cell phone, computer) to the negative current collector. The separator prevents the flow of electrons inside the battery.
In summary, lithium-ion batteries store and release energy through the movement of lithium ions between the cathode and anode, enabling the devices we rely on daily, [5, 6].

1.3. Temperature effects on EV battery performance and case studies

Temperature significantly influences the electrochemical processes occurring within EV batteries, thereby impacting their performance, efficiency, and lifespan. Extreme temperatures, both hot and cold, can have detrimental effects on battery health.
Recent researches by [7, 9] highlight the accelerated degradation of lithium-ion batteries, the main battery technology in EVs, at elevated temperatures. These studies demonstrate that prolonged exposure to temperatures above 40°C leads to increased capacity fade and impedance rise, compromising the battery's performance and longevity. Furthermore, high temperatures promote the formation of damaging side reactions, such as lithium plating and electrolyte decomposition, intensifying degradation mechanisms.
Conversely, cold temperatures slow down the electrochemical reactions within EV batteries, resulting in decreased capacity and power output. [10] elucidate the effects of sub-zero temperatures on lithium-ion batteries, revealing reduced ionic conductivity and slowed-down kinetics, which translate to reduced performance and range in EVs operating in cold climates.

1.3.1. Range and charging efficiency

1. Range Reduction

The most notorious range killer for electric vehicles is cold weather. Since the introduction of the first electric vehicles, it has repeatedly been criticized that they are not suitable for winter, [11].
The daily range is primarily influenced by the heating and cooling system. Energy from the

battery not only powers the vehicle but also the auxiliary systems, particularly:

- Heating and cooling the vehicle interior
- Heating and cooling the battery

At low temperatures, people often assume that the loss of range is due to reduced battery performance. While lithium-ion batteries do become sluggish at extreme temperatures (low temperatures affect their ability to store and release energy), this has much less impact on range than the auxiliary loads. Moreover, automakers have developed thermal management systems to keep batteries within the optimal temperature range, further minimizing the loss of battery performance.

To find this out, Geotab [11] analyzed anonymized data from 5.2 million trips from 4200 electric vehicles, representing 102 different make/model/year combinations, and examined the average efficiency of the trips concerning the temperature.

- Most electric vehicles follow a similar temperature-range curve, regardless of make or model.
- While both low and high temperatures affect range, colder climates have a more significant impact.
- 21.5°C is the optimal point with the highest efficiency.

2. Charging Time

Cold temperatures increase impedance, leading to longer charging times. Battery conductivity and diffusivity decrease, affecting charging efficiency. Hence, EVs should be above freezing point temperature before charging to optimize performance, [1], [6], 12].

Given the points mentioned above, it's understandable why batteries respond more slowly in winter. When connecting a battery-powered vehicle to the charging station, the following occurs, [13]:

- Activation of the battery heating system: Modern electric vehicles are equipped with a battery management system that regulates the temperature of the battery. If the temperature falls below a certain threshold, this system activates the heater to bring the battery to an optimal charging temperature. This protects the battery from damage due to charging at too low a temperature but also extends the charging time.
- Reduced charging efficiency: As previously mentioned, cold weather increases the internal resistance of lithium-ion batteries. When charging under cold conditions, the battery may not absorb energy as quickly, leading to reduced charging speed, especially in the initial charging phases.
- Limitations on fast charging in cold conditions: Fast charging stations at highway rest stops or shopping centers offer high power to quickly charge batteries. However, in cold conditions, most EVs limit the amount of energy they draw from fast chargers to prevent potential battery damage. While it often takes only 30 minutes to reach an 80% charge in summer, it can take significantly longer in winter.

Thus, many of modern electric vehicles offer a feature called battery preconditioning, see Section 1.3.2. below. This function warms the battery before the charging process, reducing the negative impacts of cold temperatures on charging time. However, preconditioning also requires energy, thus extending the overall charging process.

1.3.2. Battery aging and degradation

1. Accelerated Aging

High operating temperatures accelerate battery aging. Charging under elevated temperatures leads to degradation. EV batteries must operate therefore within optimal temperature ranges to maximize lifespan, [14].

2. Lithium Plating

Low temperatures cause ions to flow more slowly through battery cells. Consequently “lithium plating” occurs, disrupting energy flow and reducing power and range, [15].

1.3.3. Case studies

There are several case studies of successful EV adoption in harsh climate regions around the world, [16-18]. These case studies highlight the resilience of EVs and the effectiveness of various strategies in overcoming challenges posed by extreme weather conditions. Some striking examples in different countries are given according to [19, 20]:

1. Norway

Norway is one of the world leaders in EV adoption, despite its harsh climate with cold

winters and mountainous terrain. Government incentives such as tax exemptions, toll exemptions, and free parking for EVs have played a significant role in driving adoption.
Additionally, Norway have invested heavily in charging infrastructure, with thousands of charging stations installed nationwide, including fast chargers along major highways. The availability of all-wheel-drive EV models and advancements in battery technology have also contributed to the success of EVs in Norway's challenging climate.

2. Canada

Canadian provinces like Quebec and British Columbia have seen significant EV adoption, despite experiencing cold winters and vast distances between cities. Public and private investments in charging infrastructure, including the installation of fast chargers along major highways, have helped alleviate range anxiety for EV drivers. Government incentives such as rebates on EV purchases and subsidies for home charging installations have encouraged consumers to switch to electric vehicles.

3. Sweden

Sweden has made strides in EV adoption, despite facing similar climate challenges as Norway. In addition to government incentives and investment in charging infrastructure, Sweden has focused on promoting EVs as a sustainable transportation solution through public awareness campaigns and education initiatives. Collaborations between automakers, government agencies, and energy companies have also helped accelerate the adoption of EVs in Sweden.

4. Alaska, USA

Despite its extreme climate with long, cold winters and rugged terrain, Alaska has seen a growing interest in EVs. The state government has offered incentives such as tax credits and rebates for EV purchases, as well as grants for charging infrastructure development. Alaskan EV drivers have found ways to adapt to the climate, such as preconditioning their vehicles while plugged in to conserve battery power and investing in winter tires for improved traction.
On the other hand, effect of high temperature impact on batteries, tires, and cooling systems have been described in [21], The impact of in-cabin air conditioning (AC) on the range of electric vehicles (EVs) is minimal, especially when compared to the high-energy demands of winter heating. While AC does consume some power, it is lower than required power amount for heating during cold weather. This is due to the lower temperature gradient required in summer, as confronted in winter. Battery, tire, and cooling system performance can be affected by temperatures above 30°C. A recent study, [22] shows that even though summer weather impacts range, efficiency and performance differently from vehicle to vehicle. EV drivers can take similar steps to mitigate these effects. A study, [12] by AAA found that a car lost 36 miles of range when it was driven in 35°C heat, compared to being driven in 24°C heat. The same study also found that the same EV lost more than 62 miles of range when it was driven in –6°C heat, dropping from 105 to 43 miles of average range. Thus, one can conclude that heating the car consumes more energy than cooling it, [23]. There is usually a smaller difference between the ideal cabin temperature and the outside temperature in the summer than in the winter. The indoor temperature may need to be changed by 10 or 15°C degrees in the summer but by 40°C or more degrees in the winter, [22].
These case studies demonstrate that successful EV adoption in harsh climate regions requires a combination of government incentives, investment in charging infrastructure, consumer education, and technological advancements tailored to address specific climate challenges. As EV technology continues to evolve, the feasibility and resilience of electric vehicles in extreme weather conditions are expected to improve further.
Additionally, [24] conducted a representative test with popular EVs to investigate the impact of cold temperatures on charging performances. Within this evaluation, most of the electric vehicles considered were tested within a charging window of 0% to 100%. Compared with the manufacturers' charging time specifications, certain models were specifically examined within a charging window of 10% to 80%. In the comparative

test, all vehicles were tested once immediately after driving, with a temperature-controlled battery, and once with a cooled-down traction battery after a standing time of at least 10 hours at an ambient temperature of around 0°C without being driven in the meantime. According to the operator, the charging infrastructure selected for the tests provided a charging power of 300kW. "*The selection of test vehicles represented only a sample of currently available electric vehicles on the market. No individual ratings were given, and no test winner was determined. The vehicles were examined solely on their own, but under varying conditions, to assess their charging characteristics.*", [24]. The results can be seen in Table 1, from a smaller to bigger difference in minutes of charging time increase with various battery capacities depending on the brand and model.

1.4. Thermal management systems

As EVs gain prominence, efficient thermal management becomes crucial for optimizing performance, safety, and longevity. In this section the significance of thermal management in EVs and the strategies employed to maintain optimal temperatures will be explored.

Following aspects for thermal management solutions should be considered for an accurate battery modelling, [25]:

1. Integrated Systems

EVs incorporate thermal management systems to regulate battery temperature. These systems use heating and cooling mechanisms to keep batteries within the optimal operating range, [26].

2. Critical for Extreme Climates

Effective thermal management is crucial in regions with extreme weather conditions. Batteries must remain within the ideal temperature range for optimal performance and longevity [27].

To mitigate the adverse effects of temperature on EV batteries, advanced thermal management systems (TMS) are employed. These systems regulate the temperature within the battery pack, ensuring optimal operating conditions regardless of external temperatures. Active cooling and heating mechanisms, such as liquid cooling and electric heaters, are integrated into the battery pack to maintain temperatures within the ideal range, [27].

Cutting-edge researches by [28-30] introduce innovative thermal management strategies utilizing phase change materials (PCMs) for EV batteries. By harnessing the latent heat, associated with phase transitions, PCM-based TMS effectively stabilizes the temperature within the battery pack, mitigating thermal stress and enhancing battery performance. This research underscores the potential of PCM-based TMS in advancing EV technology and improving battery efficiency and longevity.

Furthermore, temperature fluctuations not only affect the performance of EV batteries but also influence the vehicle's range and charging behavior. High temperatures accelerate internal resistance, leading to faster battery depletion and reduced driving range. Conversely, cold temperatures impede the battery's ability to accept charge, prolonging charging times and diminishing the available range.

Other recent studies, such as those conducted by [31, 32] provide insights into the real-world implications of temperature on EV range and charging dynamics. Field tests conducted under varying temperature conditions reveal significant reductions in vehicle range, particularly in extreme climates. Moreover, charging times are prolonged at low temperatures, highlighting the importance of temperature management in optimizing EV charging infrastructure.

As already described in Section 1.3., temperature plays a critical role in determining the performance, efficiency, and longevity of EV batteries. State-of-the-art research findings underscore the importance of maintaining optimal temperature conditions through advanced thermal management systems. By mitigating the adverse effects of temperature fluctuations, such systems contribute to enhancing battery performance, extending lifespan, and advancing the transition to sustainable transportation. As EV technology continues to evolve, ongoing research efforts are essential for further optimizing temperature management strategies and maximizing the potential of EVs.

Table 1: Charging times of typical EVs under different temperature conditions from 0% to 100% battery level

Vehicle	Temperature	Charging time	% Increase of charging time	
Audi Q4 40 e-tron	preconditioned battery cold 0°C to 5°C	64 min 66 min	+2 min	+3.1%
Tesla Model 3 SR+	preconditioned battery cold -5°C to 0°C	63 min 71 min	+8 min	+12.7%
VW ID3 58kWh	preconditioned battery cold -5°C to 0°C	56 min 64 min	+8 min	+14.3%
Kia e-Niro 64kWh	preconditioned battery cold 0°C to 5°C	101 min 114 min	+13 min	+12.8%
Hyundai IONIQ 5 72.6kWh	preconditioned battery cold -5°C to 0°C	52 min 67 min	+15 min	+28.9%
Peugeot e-2008	preconditioned battery cold -5°C to 0°C	45 min 71 min	+26 min	+57.8%

2. Modelling A Lithium-Ion Battery Cell

Lithium-ion batteries are the workhorses behind our portable electronics, electric vehicles, and renewable energy systems. Understanding their behavior and accurately modelling their performance is crucial for optimizing battery-powered systems. In this section, the principles of modelling Li-ion battery cells, the significance of accurate models, and common approaches used in the field are explored.

Battery models have become essential tools for designing battery-powered systems, serving various purposes such as, [33]:

1. Battery Characterization

The initial stage in developing a precise battery model involves constructing and parameterizing an equivalent circuit that accurately represents the battery's nonlinear characteristics. Engineers use measurements performed on battery cells of the same type to determine dependencies on temperature, state of charge (SOC), state of health (SOH), and current I.

2. State-of-Charge (SOC) Estimation

Battery models help develop algorithms for estimating SOC. Modern battery chemistries require sophisticated approaches like Kalman filtering due to flat OCV-SOC discharge signatures.

3. Degradation Considerations

Batteries experience degradation over time because of calendar life and the process of charge-discharge cycles. Models assist in developing battery management strategies that account for degradation.

4. Real-Time Simulation

Hardware-in-the-loop testing of battery management systems (BMS) relies on accurate battery models. A model designed for system-level development can be reused for real-time simulation.

2.1. Equivalent circuit models

For the modelling of the equivalent circuit part of the batteries following basics of the circuit should be considered.

- Ohmic Resistance in a Lithium-Ion Battery Cell
- Charge Carrier Transit Resistance and Double-Layer Capacitance
- Solid-State Diffusion

Different types of circuit models are presented in detail in [22].

2.2. Thermal modelling

Thermal effects significantly impact battery performance and safety. A thermal model considers heat absorption or dissipation through, [23]:

- Conduction: Heat transfer within the battery.
- Convection: Heat exchange with the

surrounding environment.

• Radiation: Thermal radiation.

• Internal Heat Source: Heat generated during operation.

• Parameters like thermal conductivity, heat capacity, and emissivity coefficient are essential for accurate thermal modelling.

Furthermore, the following aspects explain the importance of thermal modelling and its challenges.

1. Temperature Impact on Battery Performance:

Battery performance is highly temperature-dependent regarding capacity, lifetime and safety, [22].

2. Key Aspects of Thermal Modelling:

• Heat Generation: During charge and discharge, batteries generate heat due to internal resistance and irreversible reactions. Heat is also produced during fast charging or high current draw. Accurate modelling requires understanding of these heat sources.

• Heat Dissipation Mechanisms: Batteries dissipate heat through various mechanisms like conduction, convection, etc. like described above. Modelling these mechanisms helps predict temperature distribution.

• Thermal Resistance and Capacitance: Equivalent thermal circuits represent batteries. Thermal resistance R_t describes how easily heat flows through the battery and thermal capacitance. C_t represents the battery's ability to store heat. The boundary conditions for those thermal modelling assumptions are i.e. external factors (ambient temperature, cooling systems) affect battery temperature. Modelling boundary conditions ensures accurate predictions.

3. Challenges in Thermal Modelling:

• Nonuniform Temperature Distribution: Batteries have varying temperature profiles due to spatial and temporal variations. Modelling must account for this nonuniformity.

• Transient Effects: Rapid charge/discharge cycles cause transient temperature changes. Transient modelling captures dynamic behavior.

• Coupling with Electrochemical Models: Combining thermal and electrochemical models is complex. Accurate predictions require solving coupled equations.

In summary, thermal modelling ensures efficient battery design, optimal operation, and safety. Researchers and engineers continue to refine models to address real-world challenges in battery technology.

2.3. Ageing model

A cell model for electrical behavior was discussed in the previous section. The chemical behavior of a lithium-ion battery cell with respect to ageing is discussed in this section, [24]. "*The reasons for battery ageing, such as lithium deposition and the formation of Solid Electrolyte Interphase (SEI), are widely studied in the literature.*" [25].

There are two forms of degradation associated with aging, loss of capacity and increased resistance. A classical empirical model was developed to model these two consequences. These models focus on simulating the ageing effects with constant conditions (SOC, temperature, current) in the long run [26], [27]. These models are usually accurate over a long period of time at steady conditions. The objective of this ageing model is to simulate instantaneous degradation of a lithium-ion battery, unlike most existing models that cannot simulate degradation over a short period of time (a few seconds), nor under evolving conditions. This is because the current and the temperature of the battery pack supply energy to the powertrain at varying rates, [28].

A cycle ageing model and a calendar ageing model are represented by two different equation packages. The ageing model switches from one ageing mode to another depending on if the vehicle is being driven or parked. Additionally, the aging factors depend on temperature, whereas temperatures around 20 °C are optimum for storage and operation of the batteries.

2.3.1. Calendar ageing

Basically, a distinction is made between calendar and cyclic aging to describe the aging of lithium-ion battery cells. Both mechanisms lead to a decrease in the capacity and performance of the lithium-ion battery cell, [29]. The decrease in performance is due to the increase in charging and discharging resistance. According to [30] the main reasons for the aging of lithium-ion battery cells are:

- Change in the morphology of the anode/cathode,
- Reduction in the active surface of the anode/cathode,
- Binder degradation at the anode/cathode,
- Irreversible intercalation of lithium at the anode (graphite),
- Corrosion of the metallic conductor (copper) of the anode,
- Electrolyte contamination,
- Separator abrasion,
- Reduction in the porosity of the separator.

According to [41,43] and [36], calendar ageing is a temperature-sensitive chemistry process that can be described by the Arrhenius law. The usual equations Eq. (1) and Eq. (2) were put into their integral form to determine the instantaneous ageing, [43]. To switch from a time scale in days to a time scale in seconds, in order to calculate the degradation effects in periods of time in the order of seconds, the equations Eq. (1) and Eq. (2) were modified into Eq. (3) and Eq. (4) respectively as follows:

$$Q_{loss}^{cal} = A_c \cdot e^{-\frac{E_{a_c}}{K_T}} \cdot t^Z \quad (1)$$

$$R_{rise}^{cal} = A_r \cdot e^{-\frac{E_{a_r}}{K_T}} \cdot t^Z \quad (2)$$

$$Q_{loss}^{cal} = \sqrt{\int_0^D \frac{1}{86400} \cdot {A_c}^2 \cdot e^{-\frac{2E_{ac}}{K_T}} dt} \quad (3)$$

$$R_{rise}^{cal} = \sqrt{\int_0^D \frac{1}{86400} \cdot {A_r}^2 \cdot e^{-\frac{2E_{ar}}{K_T}} dt} \quad (4)$$

Q_{loss}^{cal} is the capacity loss and R_{rise}^{cal} is the resistance increase due to calendar ageing. A_c and A_r are the pre-exponential factors of the capacity loss and of the resistance increase due to calendar ageing respectively. E_{ac} and E_{ar} are the activation energies of the capacity loss and of the resistance increase due to calendar ageing respectively. K is the Boltzmann constant, and T is the temperature. D is the test duration in seconds, t the time and z the power factor varying between 0.5 and 1. In the model, z is set to 0.5, [36].

With the tests performed by [44], calendar ageing data of three different types of Li-ion battery cells (18650 LFP, NMC and NCA cells) were obtained for a duration of 300 days. For each type of battery, the tests were performed on identical cells coming from the same production batch under different conditions, at 3 different temperatures (25°C, 40°C and 50°C) and 16 different SOC levels, leading to 48 different calendar ageing conditions tested for each technology, [36].

The capacity loss and resistance increase were obtained for every SOC level for the 3 different temperatures. A three linear equations system was then obtained and solved using the least squares method to determine values for A and E_a.

The results are presented in Fig. 4. The evolution of the activation energies for the capacity loss and the resistance increase, E_{ac} and E_{ar}, are shown in Figure 4 (b-c) and Figure 4 (e-f) respectively, [44].

2.3.2. Cycle Ageing

The SOH of a lithium-ion battery cell is determined not only by the calendar aging, but also by the cyclic aging. Cycling aging happens when the battery undergoes charging and discharging cycles. This aging process is affected by various mechanisms, including parasitic physicochemical transformations, which degrade the battery's energy capacity and power (impedance) capabilities, [43]. The stress factors for cyclic aging are temperature, depth of discharge DOD and current. Suppose the cyclic aging or the cyclic aging factor per cycle is known at the beginning of the battery cell tests. In that case, the aging of the lithium-ion battery cell for additional cycles can be estimated using a straight-line equation.

In the literature, cycle ageing is often described as a function of the number of cycles, [39], [38] and [36]. In this case, the simulation time also needs to be expressed in function of time, [36]. It was assumed that a cycle of cyclic ageing contains a complete discharge and a complete charge and that the difference between the charge and the discharge was neglectable. So, it was considered that the same amount of positive and negative current (stress) has the same influence on the chemical degradation of the battery.

Therefore, the ageing behavior of one cycle can be distributed over each instant. It is considered that for each cycle, the real-time is

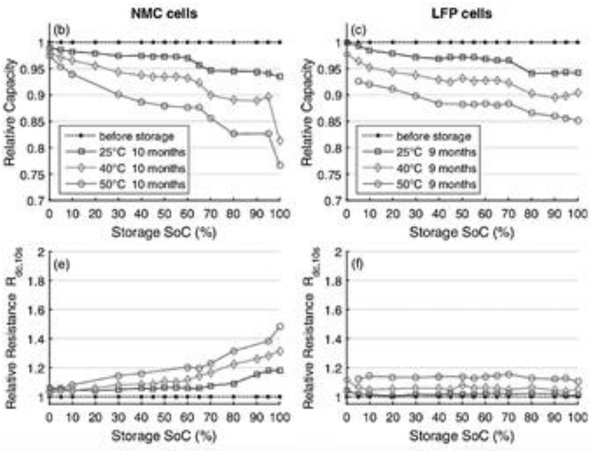

Fig. 4. Battery degradation after ca. 9–10 months of storage at various SOCs and different temperatures: (b-c) capacity fade; (e-f) rise of internal resistances, [44].

equal to two times the real capacity C_{real} divided by the current I (once during charge, once during discharge), as shown in the Eq. (5):

$$\mathrm{ds} = 2\frac{\mathrm{C_{real}}}{\mathrm{I}}3600\mathrm{dt} \quad (5)$$

Then, to change from a number of cycles to a time in seconds, the following variable change must be carried out:

$$t = \int_0^{S_{fini}} \frac{I}{7200\mathrm{C_{real}}} ds \quad (6)$$

For the cycle ageing, the rate of capacity loss and resistance increase is influenced not only by the temperature but also by the current level. Therefore, the rate of charge and discharge C_{rate} has been added into the calculation. The loss of capacity and the increase of resistance are calculated through the Eq. (7) and Eq. (8) as follows, [36]:

$$Q_{loss}^{cyc} = 2A_c \cdot e^{\left(\frac{-E_{a_c}+B_c \cdot C_{rate}}{R \cdot T}\right)} \cdot t^Z \quad (7)$$

$$R_{rise}^{cyc} = A_r \cdot e^{\left(\frac{-E_{a_r}+B_r \cdot C_{rate}}{R \cdot T}\right)} \cdot t^Z \quad (8)$$

Q_{loss}^{cyc} is the capacity loss and R_{rise}^{cyc} is the resistance increase due to cycle ageing. A_c and A_r are the pre-exponential factors of the capacity loss and of the increase in resistance to the cycle ageing respectively. E_ac and E_ar are the activation energies of the capacity loss and of the resistance increase due to cycle ageing respectively. C_{rate} is the cycling rate. B_c and B_r are the current accelerating factors, that adjust the impact of the C_{rate}, of the capacity loss and the resistance increase respectively. R is the perfect gas constant; t is the number of cycles and z is a power factor varying between 0.5 and 1. From the data given in the reference [39], it was observed that cycle ageing behaviors evolved linearly with the number of cycles, so z was set to 1. After applying the variable change described in Eq. (6), the capacity loss and the resistance increase are then expressed under their integral form as followed in Eq. (9) and Eq. (10), [36]:

$$Q_{loss}^{cyc} = \int_0^{S_{fini}} A_c e^{\left(\frac{-E_{a_c}+B_c \cdot C_{rate}}{R \cdot T}\right)} \frac{I}{3600\mathrm{C_{real}}} ds \quad (9)$$

$$R_{rise}^{cyc} = \int_0^{S_{fini}} A_r e^{\left(\frac{-E_{a_\mathrm{r}}+B_\mathrm{r} \cdot C_{rate}}{R \cdot T}\right)} \frac{I}{3600\mathrm{C_{real}}} ds \quad (10)$$

S_{fini} is the cycle duration.

The parameters identification was carried out based on the data published by [45]. They found the activation energy E_{ac} and the acceleration factor A_c for a simpler cycle ageing model which doesn't consider the regime impact. They discovered that $A_c = A_r$ = 11443 and $E_{ac} = E_{ar}$ = 42570 J·mol^{-1}. Those values were reused as predefined parameters in this model. Regarding the values of B_c and B_r, they were calibrated from the data published by [39] using the least squares method. They investigated the cycle ageing behavior of a LCO cell at different cycling rates (0.5C, 0.8C, 1C, 1.2C 1.5C) at a given temperature of 25°C. From the Eq. (21) and Eq. (22), it is observed that when the regime and the temperatures are fixed, the capacity loss and the resistance increase are linear as a function of time (or number of cycles). The data from [39] allow us to determine the values of K_c and K_r, which are the slopes of the evolution of capacity and resistance respectively. They are defined as follows, [36]:

$$K_c = 2A_c \cdot e^{\left(\frac{-E_{a_c}+B_c \cdot C_{rate}}{R \cdot T}\right)} \quad (11)$$

$$K_r = A_r \cdot e^{\left(\frac{-E_{a_r}+B_r \cdot C_{rate}}{R \cdot T}\right)} \quad (12)$$

According to [46], the proposed calendar and cycle aging models imply that the degradation rate remains constant as long as the cycles are consistent. However, lithium-ion battery degradation experiments reveal a different reality. The degradation rate of lithium-ion batteries is non-linear with respect to the number of cycles. In battery aging tests, as depicted in Fig. 5, we observe the following trends:

- Early Cycles: During the initial cycles, the degradation rate is significantly high. See region A.
- Later Cycles: As the cycles progress, the degradation rate stabilizes. See region B and C.
- End of Life (EoL): Approaching the end of life, the degradation rate increases rapidly. See region D.

This observation underscores that the degradation rate of lithium-ion batteries is intrinsically tied to their current life state. [47] shows the same picture like in Fig. 5, but with a much higher degradation rate in region D and suggests that battery manufacturers do not publicize data reports for region D. Moreover, unfortunately, there are also not many tests or simulations publicly available in the literature for this region D, but mostly in region A and B only.

Lastly, according to [43] Accelerated ageing tests were performed on lithium-ion cells at 60°C to assess the impact of different SOC levels on calendar ageing and to examine the interactions between cycling and calendar ageing in electric vehicle applications. The results indicate that cycling and calendar ageing interact in complex ways, making it challenging to model both processes simultaneously. In the same research article, it is stated that the cycling ageing results are more challenging to analyze due to numerous factors and their interactions. Because during these tests, calendar ageing overlaps with cycling ageing. To isolate the calendar ageing component within the cycling ageing data, they employed a cumulative damage approach.

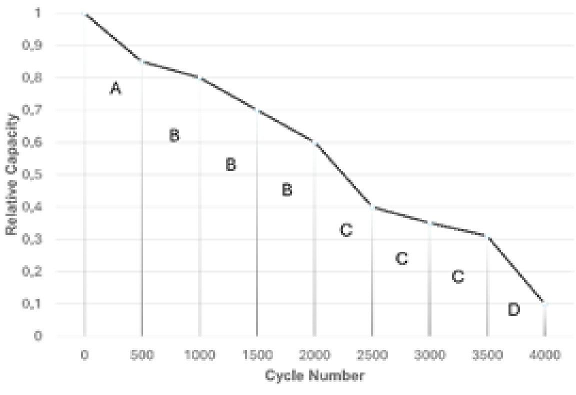

Fig. 5. General capacity degradation behavior of lithium-ion batteries.

2.3.3. Temperature ageing

The ideal temperature for any battery is around 25°C (77°F), which is considered room temperature. Manufacturer datasheets usually specify the cycle life based on this temperature. However, operating a battery at higher temperatures, especially near its maximum limit, accelerates its ageing process, [48]. The ageing factor value measures the time spent at temperatures above room temperature, with the ageing increasing as the temperature rises. The formula to calculate this factor is $F_t = h \times (0.002t^2 + 0.03t)$, where "$t$" is the temperature rise above 25°C and "h" is the battery's calendar life in hours, [8, 48].

The stress model for temperature is based on the Arrhenius equation, which describes how the rate of a chemical reaction depends on temperature [8].

$$S_T(T) = e^{k_T \cdot (T - T_{ref}) \frac{T_{ref}}{T}} \quad (13)$$

where:

$S_T(T)$ is the temperature-dependent stress factor,

k_T is a constant that represents the temperature sensitivity,

T is the absolute temperature,

T_{ref} is the reference temperature.

While the Arrhenius equation suggests that the degradation rate decreases as the temperature lowers, this relationship does not apply at low temperatures.

The authors of [9] show that the temperature of 20°C serves as a critical threshold between high and low temperature effects on battery behavior. When the temperature remains above 20°C, the battery's impedance decreases. However, if the temperature drops below 20°C, the impedance increases. Notably, calendar aging test data from this research suggests that the degradation rate at 15°C is smaller than at 20°C.

Experimental results also show that battery is aging exponentially faster when it spends its life at higher temperatures, Fig. 6.

3. Research and Tools

Researchers continuously refine battery models to improve accuracy. The first step in the development of an accurate battery model

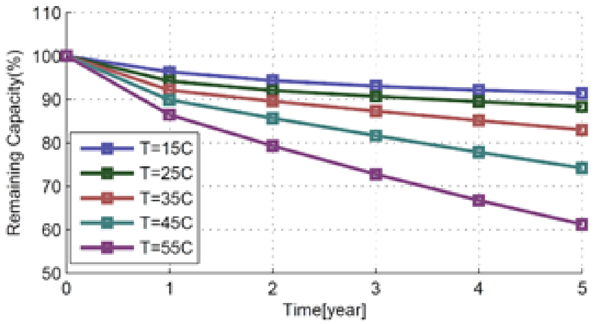

Fig. 6. Calendar aging with varying temperature at 50% SOC [9].

is to build and parameterize an equivalent circuit that reflects the battery's nonlinear behavior and dependencies on temperature, SOC, SOH, and current. These dependencies are specific to each battery's chemistry (see i.e. Section 2.3) and must be determined through measurements conducted on battery cells that are identical to those intended for use with the controller being designed, [49]. Tools like MATLAB & Simulink offer powerful capabilities for battery modelling and simulation, [49]. Academic studies explore nonlinear modelling of lithium-ion battery cells for electric vehicles, [50]. Books like Mathematical Modelling of Lithium Batteries provide in-depth insights, [51].

Briefly, modelling lithium-ion battery cells is a dynamic field with practical implications for energy storage, electric mobility, and sustainability. With advancing technology, accurate models will continue to play a fundamental role in shaping the future of battery-powered systems.

For thermal modelling tools and approaches like the following can be considered, [52]:

- Finite Element Analysis (FEA) simulates heat transfer within battery cells and packs. Accounts for geometry, material properties, and boundary conditions.
- Computational Fluid Dynamics (CFD) help to make models fluid flow and heat transfer in battery cooling systems. Useful for electric vehicle battery packs, [53].
- Multiphysics Simulation Tools like ANSYS and MATLAB & Simulink offer multiphysics capabilities for thermal modelling. Furthermore, coupling with electrochemical models is feasible, [52].

In summary, thermal modelling ensures efficient battery design, optimal operation, and safety. Researchers and engineers continue to refine models to address real-world challenges in battery technology.

4. Conclusions and Outlook

In this article, types and the theoretical mechanism of ageing are presented. Additionally, the effects of temperature have been discussed. Battery aging in electric vehicles (EVs) is significantly influenced by temperature. High temperatures accelerate degradation by increasing chemical reactions, leading to capacity loss, while low temperatures slow down electrochemical processes, reducing performance. Both extremes can shorten battery life, making thermal management systems crucial for maintaining battery health. Understanding this relationship is key to optimizing EV range and longevity. Future battery technologies like Solid-state batteries (SSBs) are emerging as a promising alternative to traditional lithium-ion batteries. By replacing the liquid electrolyte with a solid electrolyte, SSBs offer potential benefits, including higher energy density, improved safety, and reduced risk of thermal degradation. They are less sensitive to temperature fluctuations, potentially enhancing performance and lifespan in extreme conditions. As research advances, solid-state batteries could revolutionize EV technology by offering longer driving ranges, faster charging times, and more durable solutions compared to current lithium-ion systems. While still in development for series production in big scales, solid-state batteries could revolutionize the EV industry by providing longer-lasting, more efficient, and safer energy storage solutions.

CRediT authorship contribution statement

Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Declaration of competing interest

The authors declare there is no conflict of interest in this study.

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