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Real-world electric bus operation: Trend in technology, performance, degradation, and lifespan of batteries

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CONTENTS

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HIGHLIGHTS

- The pace of bus electrification is increasing in order to decarbonize the public transportation system. Lithium-ion batteries form the most valuable component of an electric bus from a cost and performance point of view.
- The lifespan of an e-bus battery is reduced due to accelerated battery degradation under non-optimal operating conditions. Temperature extremes induce battery ageing, impacting the e-bus operational capacity, safety, and replacement ratio. This can spike the total cost of ownership, compromising the economic viability of e-buses.
- Availability of real-world operational data for e-buses is limited globally, and almost absent in India. This paper analyzes cell-level experimental data for popular battery technology on degradation under variable conditions and compares it with real-world case studies, to deduce scenarios for best performance under Indian climatic conditions.
- For a given route, the battery sizing and charging strategy should consider the energy consumption requirement and efficiency of an e-bus. The battery pack must be equipped with an efficient thermal management system to maintain optimum battery temperature.
- In batteries, an advanced battery management system must be used for real-time monitoring and data collection. Data availability will be crucial for developing required standards, regulations, and testing ecosystems to ensure the adoption of best practices.

EXECUTIVE SUMMARY

Context

The transport sector is one of the fastest-growing carbon emitters and a leading cause of air pollution in major cities and in need of interventions for decarbonization. Electrification of buses is necessary for eliminating tailpipe emissions, and building a clean and low-carbon public transportation system. Several countries across the world are accelerating e-bus adoption through enabling policies, tax incentives, and subvention. However, challenges such as upfront cost of e-buses being twice or thrice that of internal combustion engine (ICE) buses, range issues, bottlenecks in the supply chain, and under-developed charging infrastructure stand in the way of large-scale adoption of e-buses across the world.

In e-buses, batteries account for 40–50 percent of the total upfront purchase cost and form the most critical component of the e-bus powertrain. The performance of e-buses also depends on the batteries, which degrade faster under non-optimal usage. For example, the ideal lifespan of lithium-ion batteries (LIBs) in the e-bus application should be 5–7 years. However, the batteries' lifespan is affected tremendously by non-optimal conditions of temperature, state of charge (SoC), charging rate (C-rate), and depth of discharge (DoD). Factors, such as driving behavior, auxiliary consumption, road quality, passenger load, speed, topography, and climate, influence the energy consumption per kilometer, which in turn impacts the driving range per charge of the e-bus. While stakeholders are already planning to overcome bottlenecks associated with range and energy consumption, accelerated battery degradation will affect battery capacity, further reducing the driving range per charge of the e-bus. This would lead to frequent charging requirements to achieve the desired daily trip length. Moreover, rapid degradation will push an e-bus battery to complete its automotive life (i.e., 20 percent capacity loss compared to its rated/original capacity) much before its ideal lifespan, requiring a higher number of battery replacements per service life. As the e-bus market develops across the world, a high-level assessment of the reduction of battery life and efficiency due to accelerated battery degradation in e-buses running under non-optimal conditions is necessary for improving their feasibility.

About this paper

With this paper, we aim to familiarize original equipment manufacturers (OEMs), state road transport undertakings (SRTUs), and other key stakeholders with the factors that accelerate battery degradation and its impact on the performance and economic viability of e-buses. This understanding will help stakeholders to optimize the e-bus operation, minimize battery degradation, and improve the energy efficiency per kilometer (km) of travel. This will further help in selecting the best operating scenarios, optimizing battery sizing and charging requirements, and improving battery life.

In this working paper, we identify specific battery technologies preferred for powering e-buses in different geographical locations across the world and assess their performance under different environmental conditions. The paper studies how different stress factors contribute to ageing of batteries and their overall impact on the automotive life of e-bus batteries. This paper also assesses how this battery degradation can affect the battery and e-bus performance in the near term, and the battery life and economic viability of the e-bus in the long term. This analysis is followed by a series of recommendations to adopt best practices, improve planning, and devise policy, which will be instrumental in improving battery lifespan in countries like India, which are planning for large-scale adoption of e-buses for public transport.

The e-bus ecosystem is still developing in India; therefore, the local battery pack-level data on the impact of different stress factors on battery life is unavailable in the public domain. Hence, we have adopted a literature review and desk research path to analyze global data on e-bus battery degradation at the cell level (taken from experimental and simulation-based studies) and have correlated the same with the available pack-level real-world case studies from different geographical regions with varying operating conditions. As the global real-world scenarios can be different from those in India, we recommend collecting region-specific pack-level data to develop customized strategies to improve battery life.

Key findings

- Globally, battery chemistries, such as lithium iron phosphate (LFP), lithium nickel manganese cobalt (NMC), lithium titanium oxide (LTO), and lithium manganese oxide (LMO) have found space in e-bus applications where LFP and NMC variants are most widely used. Globally, NMC batteries are preferred for regions with long duty cycles, whereas LFP batteries are chosen in regions with shorter duty cycles.
- NMC batteries have high energy density but are sensitive to high C-rates, where fast charging can reduce their lifespan by 10 percent compared to overnight slow charging. LFP batteries have high cycle-life, high DoD tolerance, and thermal stability but lower energy density than NMC batteries. LTO batteries show higher stability for flash and fast charging. The desirable range of an e-bus is achieved by sizing a battery optimally and choosing a suitable charging strategy to meet bus route energy consumption requirement.

- The lifespan of e-bus batteries depends on calendar ageing and cyclic ageing, which in turn lead to capacity fade and power fade. While high ambient temperature (> 30°C) and high SoC (> 80 %) accelerate calendar ageing, high depth of discharge (>80 %), the extreme operating temperature of the batteries, and high C-rates accelerate cyclic ageing.
- The degradation trend of batteries suggests that a battery degrades the most during the initial years due to initial high calendar ageing, especially in regions that experience high-temperature extremes. Degradation rate due to cyclic ageing is affected by both high and low temperature extremes and is consistent throughout the battery lifespan. The capacity of the LFP battery degrades to 80 percent (i.e., end of automotive life) in 4,000 cycles at 25°C and in 2,000 cycles at 45°C. Similarly, the NMC battery completes its automotive life in 1,200 cycles at 34°C and in 500 cycles at 46°C.
- Drive range per charge of an e-bus depends on both traction and auxiliary power requirements where external factors like temperature, topography, and driving behavior affect the energy efficiency. Battery degradation induces capacity fade, which reduces e-bus drive range by 26 percent over its automotive life. This in turn requires frequent charging to finish the desired trip, further increasing energy demand on a route.
- Increase in the charge time in a day will reduce the service time of e-buses, affecting the operational efficiency. This will lead to a requirement of larger number of e-buses to reach the operational efficiency of diesel buses, unbalancing the replacement ratio at a city level.
- A 20 percent reduction in battery life due to accelerated battery degradation leads to an increase in the total cost of ownership (TCO) of an e-bus by 2.2 percent. Further, the TCO of an e-bus increased by 13–30 percent as the distance the e-bus could travel decreased by 10–30 percent (due to reduced battery life).

Key recommendations

Based upon observations made and insights obtained, we have developed the guidance on maintaining optimal battery life.

Operational recommendations

- **State of charge and temperature management to reduce calendar ageing:** The e-bus should not be parked for a long time under high ambient temperature (>30°C), especially when under a high SoC of the battery (>50%).
- **Charging and discharging strategy to reduce cyclic ageing:** The battery pack should neither be overcharged (>80% SoC) nor over-discharged (<20% SoC) and must be charged at an optimum C-rate and temperature, which can be ensured by implementing a charging strategy suitable for the battery chemistry.
- **Adopting the right charging technique:** Except for LTO variants of LIB, fast charging should be avoided for other commercial variants of LIBs when possible, especially when charging in low-temperature conditions.

Planning recommendations

- **Battery sizing and charging strategy:** Using parameters such as energy consumption per km and route length for optimum battery sizing for e-buses. Planning adequate opportunity charging infrastructure along with depot charging can help in maintaining the SoC and DoD of batteries at optimal levels, thereby improving their lifespan.
- **Degradation cost in TCO estimation:** Battery wear cost and opportunity charging cost contribute to the operational cost of an e-bus and therefore should be included in the TCO estimation.
- **Circular economy in e-bus business models:** After the end of the automotive life of the battery, the battery should go for reuse and recycling to generate additional profits, reducing the TCO per km of e-buses, and ensuring the efficient utilization of resources.
- **Driver training:** Drivers must be trained for energy-efficient driving. The training must include equipping the drivers with the basic knowledge of the technology, driver simulator training, and on-road training. This will reduce trip energy consumption and ensure good battery health in the e-bus application.

Technical recommendations

- **Efficient BMS and TMS for battery:** In tropical and subtropical regions, an efficient battery thermal management system (TMS) must be deployed to maintain the battery temperature under optimal range. Also, an advanced battery management system (BMS) must be installed for real-time monitoring of battery health and recording of data for detailed analysis.
- **Regenerative braking system adoption:** Drive range uncertainty can be reduced with optimized energy consumption for traction in an e-bus drive cycle. Adoption of a regenerative braking system will cover the energy loss during deceleration in a driving cycle and transfer it to the powertrain to recharge the battery, improving the energy efficiency per km (10–15%).

- **Technical performance and efficiency:** The e-bus must be equipped with an intelligent energy management system (IEMS) to monitor and regulate auxiliary energy demands, and an eco-driving assistance system (EDAS) to ensure energy-efficient driving.

Policy recommendations

- **Battery data collection and management:** A policy and regulatory framework to facilitate an active collaboration among stakeholders for battery data collection, management, and sharing can help researchers, e-bus operators, and OEMs, analyze e-bus battery operational data, devise best operating practices, and come up with innovate solutions to minimize battery degradation under different operating conditions.

- **Standards, regulation, and testing:** With the availability of India-specific data, fit-for-purpose standards can be adopted where C-rates, DoD, and temperature match the local operating conditions. The battery durability testing under these conditions will estimate battery ageing and impact on cycle-life of the e-bus batteries in specific regions with higher precision.

INTRODUCTION

Over the last few years, multiple sectors across the world have pledged various decarbonization initiatives in a race to achieve net-zero goals. Development of a low-carbon transportation system has emerged as one of the top priorities for all major economies of the world in their fight against climate change and air pollution. For the low-carbon movement of passengers, switching to electric mass-transit vehicles such as electric buses (e-buses), which offer zero tailpipe emissions and 35 percent (ITF 2023) lower lifecycle emissions than diesel buses, is gaining significant attention.

E-buses account for 18 percent of the global bus fleet (IEA 2022), with China dominating the space, followed by Europe, India, Southeast Asia, and the USA (IEA 2023). Governments across the world have laid out support in the form of policies, incentives, and subsidies for faster penetration of electric buses in the public transportation system. China has introduced a slew of initiatives, including New Electric Vehicle (NEV) subsidy programme, NEV credit mandate, policies promoting EV charging infrastructure, and city-specific targets for accelerating e-bus adoption. Europe has set optimistic targets for e-mobility under the European Green Deal, and is accelerating e-bus adoption under the EU Sustainable and Smart Mobility Strategy and Action Plan to achieve the target of 100 percent zero-emission buses. India targets to achieve 40 percent annual e-bus sales by 2030 with flagship initiatives such as Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME) II scheme as part of the National Electric Mobility Mission Plan (NEMMP) 2020. After announcing the world's largest e-bus procurement tender for deploying 5,450 units under the Grand Challenge (an initiative to create homogenized demand across nine cities), the state-run Convergence Energy Services Limited (CESL), is further developing a roadmap to expand the e-bus network in tier-II cities under the National Electric Bus Program (NEBP) to roll out 50,000 units in the next 7–10 years. In this direction, CESL has floated its first tender for procurement of 5,690 buses under NEBP. Moreover, with the onset of the scheme named Prime Minister E-bus Sewa, government is planning to deploy 10,000 e-buses in the regions with underdeveloped organized bus services (PIB 2023).

Despite the policy support, e-bus adoption is still limited in India due to capex costs being two to three times higher than internal combustion engine (ICE) buses, under-developed charging facility, range uncertainty, and the gap between theoretical and actual service life of e-buses. As the operational costs are significantly lower in e-buses, the total cost of ownership can be reduced with the adoption of business models that reduce these capex costs; lower technical and financial barriers associated with the vehicle, battery, and charging infrastructure; and introduce risk-sharing mechanisms among stakeholders. The leasing model is developing as an alternative to the outright purchase model for e-bus procurement to address the bottlenecks associated with the e-bus and its battery component. For example, in the battery subscription model, lithium-ion batteries (LIBs), which form 40–50 percent of the e-bus cost, are leased out separately, to reduce the upfront cost of the e-bus. It should be noted that the sustainability of these business models depends on the performance and lifespan of the battery, which further depends on multiple attributes. Typically, an e-bus battery has a lifespan of 5–7 years but when subjected to non-optimal operating conditions, including ambient temperature extremes, aggressive driving, and charging behaviors, these batteries can undergo rapid degradation, reducing their life and efficiency. Therefore, having an in-depth knowledge of the impact of these external stress factors, such as temperature, state of charge (SoC), depth of discharge (DoD), and charging rate (C-rate) on battery ageing, is necessary to reduce degradation and improve battery life. This requires region-specific real-world pack-level operating data of an e-bus battery.

While real-world data on battery operation are fragmented in countries such as China, Europe, and the USA, which are leading in e-bus adoption, data are unavailable in India due to the nascent stage of the domestic ecosystem and inhibitions around sharing data. Here, assessing the laboratory-based research about the performance and life of batteries under different stress conditions and comparing the results with available real-world global data can help in identifying the optimum conditions to achieve the ideal life span of the battery in e-buses. In this working paper, we have analyzed the emerging global trend in battery technology for e-bus application, and the cell-level degradation trend in selected battery chemistries and reviewed case studies from across the world to understand accelerated e-bus battery degradation under non-optimal conditions and its consequent impacts on e-bus operation and economic feasibility. Further, we have identified the best scenario for the optimum battery life in e-bus applications, especially for e-buses operating in tropical environments like India's. Finally, we have suggested strategies to achieve optimal battery life in e-buses, emphasizing on real-world local data collection to further optimize the e-bus operational strategies in India and across the world.

RESEARCH DESIGN AND METHODOLOGY

In this study, we have conducted an in-depth literature review and data analysis to identify the impact of various stress factors on the battery life and performance of an e-bus. Further, we have analyzed the potential implications of battery degradation on different stakeholders in the ecosystem, including SRTUs, OEMs, e-bus operators, and e-bus users. Overall, we explore the following research questions for developing this working paper:

- Which battery technologies are preferred for powering e-buses in different geographical locations across the world?
- How do different e-bus batteries function in different environmental and operating conditions, and what is their impact on energy consumption and battery life?
- What is the role of different degradation mechanisms in the overall battery degradation rate in e-buses?
- What are the short-term impacts of battery degradation on e-buses and how do they affect a business model's economic viability in the long run?
- What kind of planning and policy-level interventions can help in achieving the optimal battery life for sustainable e-bus business models?

Review of battery technologies in e-bus applications

Multiple variants of lithium batteries are available for electric vehicle (EV) applications globally. We adopted a literature review and desk research path to collect secondary data from reports, technical papers, scholarly articles, magazines, and blogs. We conducted a search using academic search engines such as Google Scholar with several combinations of keywords such as 'battery type in e-bus', 'battery cell form factor', 'cell design', 'battery degradation', and so on, along with a deep Google search for other online content. We collated data on battery chemistries used by e-bus companies in different regions leading e-bus adoption across the globe.

We have encapsulated qualitative data from studies such as the one by Olsson, Grauers, and Pettersson (2016) on the trade-offs between battery size (large and small) and charger utilization (slow charging and frequent high-power charging). Finally, we have identified factors affecting energy consumption in an e-bus, which is important for selecting a suitable battery size and charging strategy for an e-bus.

Battery degradation data analysis

In battery packs, multiple cells are packed together to achieve the required capacity of an e-bus, where these cells are available in different chemistries and form factors. These battery packs undergo degradation on both cell level and pack level over time. Although cell-level degradation data, both experimental and simulation, for different battery chemistries used in e-buses are available in scholarly articles, the availability of real-world pack-level battery degradation data is limited due to the nascent stage of the e-bus ecosystem globally. Therefore, quantitative and qualitative data were analyzed for cell-level degradation analysis, while qualitative data were used for pack-level analysis. To get an insight into the degradation mechanism in different battery chemistries, we analyzed the experimental, simulation, and mathematical model-based research data at the cell level.

We could comprehend the cell-level interplay between stress factors such as temperature and SoCs, and an overall degradation in different battery chemistries by analyzing data available in multiple research articles (Keil et al. 2016; Saxena et al. 2015; Ouyang et al. 2016). For the lifespan of battery packs with different chemistries, we analyzed the data reported in various reports and research articles. For example, we reviewed a case study by Al-Saadi et al. (2022), which uses simulation data, both qualitative and quantitative, from three cities in Europe; namely, Barcelona, Osnabrück, and Gothenburg. Based on the above analyses, we have given insights into the best and worst scenarios for battery life, and possible strategies to achieve optimum battery life in e-bus applications in the latter sections.

Assessing impacts of battery degradations

Due to the lack of real-world data specific to Indian operating conditions for identifying the barriers in the operation of e-buses, we have reviewed qualitative data from different regions of the world about the immediate impacts of high battery degradation on battery sizing, energy efficiency of e-buses, range estimation, vehicle downtime, and replacement ratio. For example, we have reviewed the observations of a study by Mcgrath et al. (2022), which assesses the consequence of degradation on the range, charger utilization, and e-bus battery sizing in the United Kingdom (UK).

To get an insight into the long-term impacts of battery degradation, we reviewed studies and analyses related to the total cost of ownership (TCO) of e-buses. A TCO analysis helps in determining the operating cost of the vehicle per km, taking into consideration various parameters such as the capital cost of the vehicle including taxes, the lifetime operating cost, and battery replacement cost. We have used our previously reported TCO method (Kumar and Chakrabarty 2020) to evaluate the effect of upfront battery cost on TCO per km of e-buses, and its comparison with the diesel bus variants.

Limitations of the study

We have gathered reported data on impact of operating conditions on battery life from lab-based research and case studies. In some cases, we have extrapolated the data to understand the trend in battery life. The case studies on operating conditions for various battery chemistries in different states of the USA (Yang et al. 2018), Chinese cities of Zhengzhou and Shenzen (Li et al. 2020, Applied Energy) and European cities of Barcelona, Osnabrück, and Gothenburg (Al-Saadi et al. 2022) compare battery degradation at pack level under various temperature ranges and SoC. We have used both these cell-level data and pack-level case studies to understand the possible trends of degradation, which can aid in the development of best e-bus operating conditions in India. Due to lack of reported data for battery degradation in India, the effect of actual usage of e-buses on battery degradation can be dissimilar to what the study has noted, requiring detailed analysis to assess the exact picture of battery life and degradation in the Indian operating conditions.

BATTERY TECHNOLOGIES FOR E-BUSES

This section highlights the performance trends of different battery technologies used for e-buses operating in different geographical regions.

Battery technologies for e-bus application

Over the years, rapid technological advancements in lithium-ion batteries (LIBs) have made them a preferred choice for EV applications. LIB performance and energy efficiency can vary based on battery cell chemistry, battery cell format, and cell-to-battery packaging.

Battery cell chemistry

Based on cathode chemistry, LIBs come in different variants, such as lithium iron phosphate (LFP), lithium nickel manganese cobalt (NMC), lithium manganese oxide (LMO), and lithium nickel cobalt aluminium oxide (NCA) or anode chemistries like graphite or lithium titanium oxide (LTO). While these battery chemistries are competing to find applications in various EV segments, LFP, NMC, and LTO variants are emerging as suitable options for e-buses due to their relatively better performance.

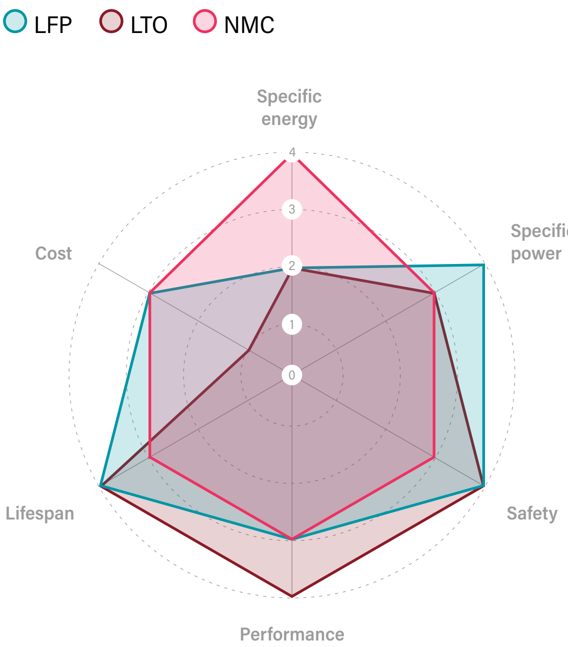
Table 1 | **Comparison of electrical parameters of lithium-ion cell variants used in e-buses**

PARAMETERS	LFP	NMC	LTO
Cell voltage (V)	3.2	3.6	2.3
Energy density (Wh/kg)	115–146	165–175	76–77
Charge rate (C-rate)	1C	0.7–1C	4C–10C
Cycle life (at 100% DoD)	3,600	3,000	10,000–20,000
Discharging temperature (°C)	-30–55	-20–55	-30–55
Charging temperature (°C)	-20–55	0–55	-20–55
Safety (thermal runaway)	High (270°C)	Low (210°C)	Highest (280°C)
Battery cost per kWh	Low	Medium	High

Source: Baumann et al. 2017; Göhlich et al. 2019.

Among LFP, NMC, and LTO variants (Table 1, Figure 1), NMC cells offer high energy density, providing a relatively higher drive range per charge, resulting in smaller and lighter battery packs. LTO chemistry on the other hand has the lowest energy density, requiring bigger and heavier battery packs to achieve the desirable range. NMC cells have lower thermal endurance and the high cobalt content makes them relatively less environmentally friendly and expensive compared to LFP cells. Among the three LIB variants, the cycle life of LTO cells is the highest, and that of NMC cells is the lowest. The high C-rates and excellent thermal stability characteristics of LTO cells make them feasible for frequent opportunity charging and ultra-fast charging, which in turn can help in substantial reduction of charging time. Moreover, stability to high C-rates makes LTO batteries more suitable for regenerative braking[1], improving their energy efficiency. Also, the better cold-temperature performance of LTO battery compared to LFP and NMC batteries makes LTO a good choice of battery in regions where cold start-ups are required. Despite their superior performance, the high material cost of LTO batteries is among the major challenges in their large-scale adoption in the e-bus market. LFP batteries have the least material criticality of the three options and offer promising energy density, cycle life, and thermal stability at an economical price tag, making them popular in cost-sensitive markets like India (Carrilero et al. 2018).

Figure 1 | **Comparison of different types of Li-ion batteries used in e-buses**

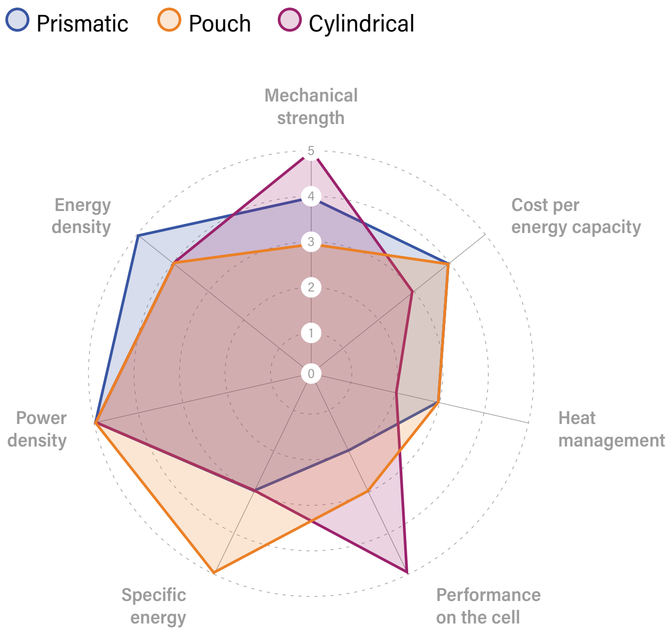


Source: Miao et al. 2019.

Battery cell design

Battery cells can further be distinguished into pouch, prismatic, and cylindrical cells, based on form factor and casing material (Figure 2). Prismatic cells store the highest energy density at present, have better packaging efficiency due to their compact size, bear high mechanical stresses from their cover, and have a simpler battery management system design. These features make them the most suitable cell format for e-buses. Among other popular cell designs, pouch cells do not have a strong, hard case, but the weight is 20 percent lower than that of prismatic cells of the same capacity, and the capacity is ~50 percent higher than prismatic cells of the same volume (Chen 2022). Cylindrical cells are easy to manufacture, and their design is transitioning from lower volume 18,650 cells (18mm diameter x 65mm length) to higher volume 21,700 (21mm diameter x 70mm length) battery cells, which increases energy density by 30 percent at the cell level and 20 percent at the pack level. Further, introduction of the 46,800 cylindrical cells will increase the cell capacity by five times and power by six times, compared to the 18,650 cells, which could popularize them in e-bus application in future. In 2021, prismatic cells dominated the LIB cell manufacturing in China, pouch cells dominated the LIB cell manufacturing in Europe and Korea, whereas cylindrical cells accounted for the majority share in LIB cells manufactured in USA and Japan (Neef 2022).

Figure 2 | **Comparison of different cell designs**



Source: Authors' analysis.

Battery pack design

Batteries are made of multiple individual cells packed together in different configurations. Inefficient packaging leads to a reduction of specific energy density (Wh/kg) from cell to pack level (Figure 3), leading to a reduction in range and increase in the volume of battery packs. It's observed that the LFP battery pack allows a better cell-to-pack level efficiency compared to the NMC battery variant (approximately 28 percent and 33.3 percent reduction in energy density from cell-to-pack level for LFP and NMC cells, respectively). This is due to the enhanced safety of LFP cell chemistry allowing battery packs to be constructed with more densely packed cells (QuantumScape 2021). Innovative blade batteries, introduced by EV manufacturer BYD Motors, increase space utilization by 50 percent (due to the unique cell-to-pack design), resulting in better cell-to-pack efficiency compared to the conventional LFP batteries (BYD. n.d.A).

In brief, battery cell chemistry can be selected based on desired key performance indicators (KPIs), cost factor, lifespan, and charging requirements (Annex A). Further, cell-to-packaging efficiency can be improved by optimizing battery space utilization. This is critical for limiting the reduction in a battery's energy density.

Emerging trends in battery technology selection

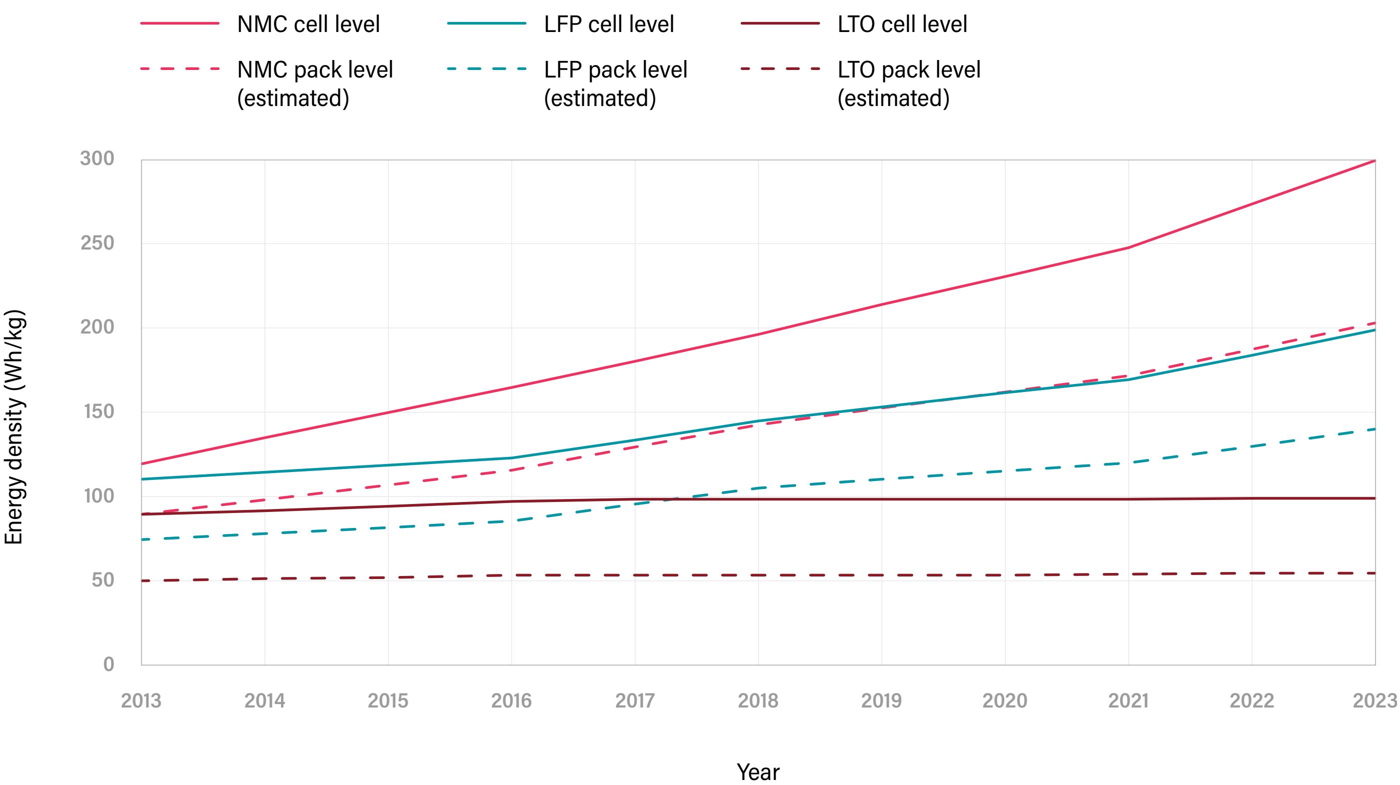
The global trends for popular battery technologies suggest that NMC and LFP variants are favorable to e-bus OEMs. A snapshot of trends in major global markets for e-buses is given below:

China

China dominates the global e-bus market, with an annual sales share of around 85 percent as of 2022 (IEA 2023), with cities like Shenzhen, Tianjin, and Zhengzhou having achieved 100 percent bus fleet electrification (Yiyang and Fremery 2022).

In China, the e-buses tend to operate on a shorter duty cycle, averaging 174.4 km (Xiao 2019, ITDP 2018), compared to the USA (200–250 km), due to its densely populated cities. This helps in prioritizing the cost factor over energy density, resulting in the predominant use of LFP battery packs. The average mileage of running an e-bus in the Chinese city of Macao is 1.73 kWh/km (Al-Ogaili et al. 2021), which is crucial for sizing a battery and charging infrastructure suitable

Figure 3 | **Comparison of specific energy density from cell to pack level**



Source: Sustainable Bus 2021 A.

for the vehicle operation. Moreover, the higher safety factor compared to that of NMC batteries makes LFP batteries the choice in heavy-duty e-buses in this region.

Table 2 shows two of the largest e-bus manufacturers in China in terms of market share, accounting for 41 percent of the sales share in 2020 (Sustainable Bus 2021 B). These manufacturers use LFP batteries in their buses, suggesting that the LFP battery is the dominant variant used in China. In 2018, the two biggest battery manufacturers, BYD Motors and Contemporary Amperex Technology Co. Limited (CATL), together sold 78 percent of the e-bus batteries containing LFP variants (Sustainable Bus 2021 B).

North America

The USA is the biggest market in the North American region, with 3,533 e-buses operating as of 2021 whose deployments are largely reflective of policies in California (aiming for bus sales to be 100 percent electric by 2029) (IEA 2023). Canada accounted for a total stock of 850 e-buses as of 2022 (IEA 2023). With sparsely populated cities and towns, states like Ohio need large duty cycles and consume 1.35 kWh of energy per km (Al-Ogaili et al. 2021). Hence, NMC batteries, which have high energy density compared to LFP and LTO batteries, dominate the market. Table 3 shows some of the major e-bus manufacturers in North America. New Flyer's indicates that an e-bus can allow a battery capacity of up to 818 kWh using NMC batteries. These are the best suited to provide the required range in sparsely populated cities and towns of the USA.

Europe

As of 2022, over 11,000 e-buses ply in Europe, with the Netherlands, France, Germany, and the United Kingdom dominating the e-bus markets, accounting for more than half of the total e-buses in the region (IEA 2023).

European cities have high population density, and bus routes are often shorter, with more frequent stops and starts (Sustainable Bus 2019), requiring higher energy consumption of up to 1.9 kWh, depending on weather (Graurs et al. 2015). The need to maximize energy recuperation requires a battery with a higher C-rate, leading to the predominant use of LFP batteries in this region, as shown in Table 4. Apart from the conventional LIBs, Europe e-bus manufacturer Irizar uses a sodium nickel chloride (also known as zebra) battery for the traction application. It’s a low-cost alternative for LIBs and can be completely discharged without causing any stress on

Table 2 | **Battery type and specifications used by manufacturers in China**

BUS MANUFACTURER	BATTERY TYPE	BATTERY SIZE (kWh)	RANGE (km)
Yutong	LFP	295	220
BYD	LFP	324 (C9)	250

Source: Yutong; BYD 2022.

Table 3 | **Battery type and specifications used by manufacturers in North America**

BUS MANUFACTURER	REGION	BATTERY TYPE	BATTERY SIZE (kWh)	RANGE (km)
BYD	Los Angeles	LFP	215 (K 7m) 446 (K9MD)	254 326
Proterra	California, Southern California, Washington DC, Dallas	LTO/NMC	79–105 450 675	80–100 386 529
New Flyer Industries	Canada, California, New York	NMC	350 440 525	280 342 404

Source: Johnson et al. 2020; BYD 2022.

Table 4 | **Battery type and specifications used by manufacturers in Europe**

BUS MANUFACTURER	REGION	BATTERY TYPE	BATTERY SIZE (kWh)	RANGE (km)
BYD (and ADL)	UK	LFP	348	257
Volvo	Sweden, Netherlands, Oslo	LFP	250	-
VDL Bus and Coach	Belgium, Amsterdam, Scandinavia	LFP	216-420	-
EBUSCO	Netherlands	LFP	400	350
Solaris	Poland, France, Italy, Germany, Lithuania	LFP	250	-
Irizar	Spain, Luxembourg, Italy, Frankfurt, Orléans	Sodium nickel technology	376 (i2e 12m)	220

Source: BYD 2021; Pagliaro and Meneguzzo 2019.

the health of the batteries compared to LIBs. However, the zebra battery has comparatively less energy density than LIBs, uses its own capacity to maintain internal temperature, and has a higher environmental footprint, making it less popular (Sawle and Thirunavukkarasu 2021; Battery University 2010)

India

The Indian e-bus market is particularly cost sensitive, requiring batteries to deliver high KPIs and safety parameters while being affordable. This makes LFP and NMC batteries popular choices among other LIB variants. Moreover, the better thermal stability of the LFP battery pack under the hot and humid conditions of this region makes it a favorable choice. Table 5 shows some of the key players in India's e-bus manufacturing space and the respective battery technologies they use.

In short, our analysis suggests that in various regions across the world, e-buses running on longer routes are generally equipped with NMC batteries due to their higher specific energy density and driving range, while those plying shorter distances use LFP or LTO batteries (also suitable for fast/flash charging) due to their higher C-rate capability (Biczel and Kwiatkowski 2018). Therefore, one way for India to incorporate diverse battery chemistries in its e-buses can be based on duty cycles.

Battery sizing planning

Planning optimal battery sizing is vital for an e-bus to complete its scheduled service in a day. Several trade-offs are associated with battery sizing, cost, and charging requirements in an e-bus. Figure 4 shows the layout of battery sizing with

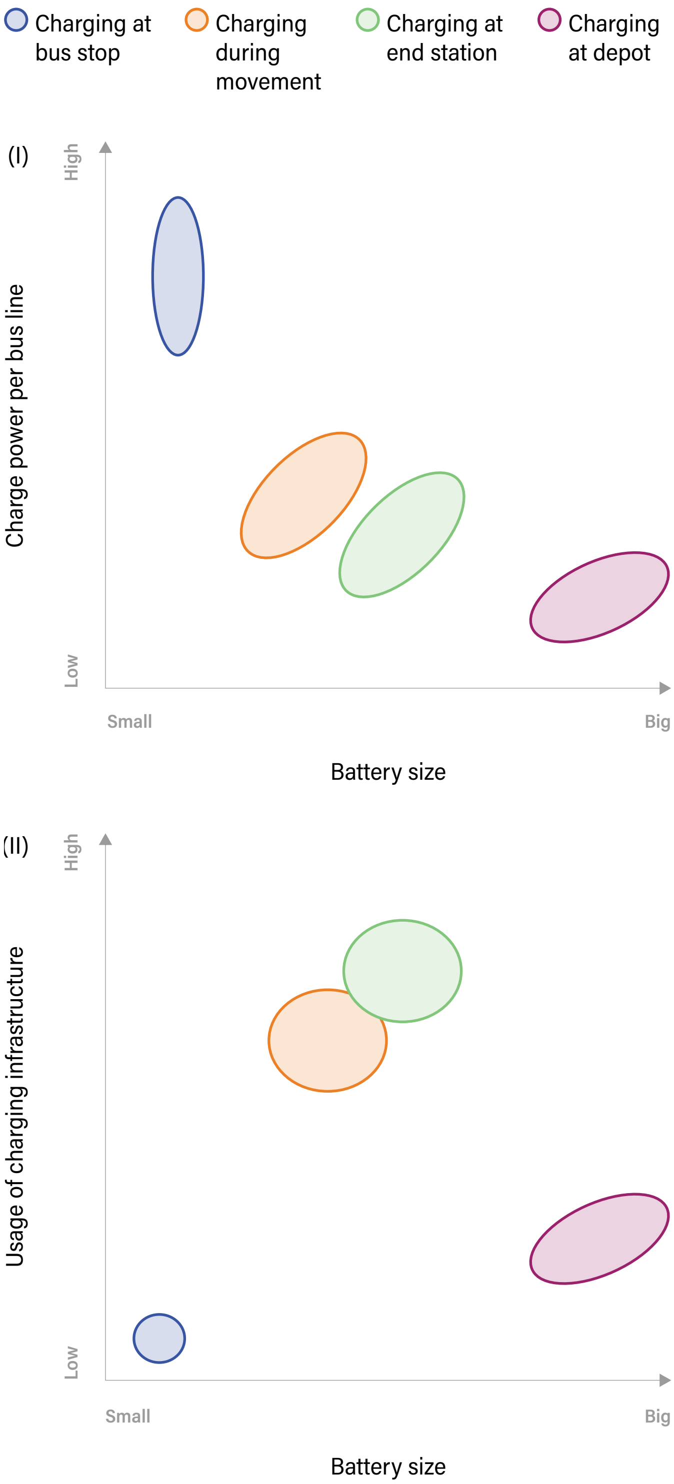
Table 5 | **Battery type and specifications used by manufacturers in India**

BUS MANUFACTURER	BUS TYPE	BATTERY TYPE	BATTERY SIZE (kWh)	DECLARED RANGE (km)
Olectra BYD	Standard	LFP	342	300
	Midi		200	200
	Mini		135	200
PMI Foton	Standard	LFP	150	144
	Midi		150	168
	Mini		102	-
Tata Motors	Standard	NMC	260-350	160-220
	Midi		176	150
JBM Solaris	Standard	NMC	200	200
	Midi		196	250
Switch Mobility	Standard	LFP	389	390

Source: TUMI and C40 Cities 2023; Pandya 2023; Switch Mobility 2022.

respect to charging power and charger utilization per day. Buses with smaller batteries have lower costs and high energy efficiency but fall short of the desirable range, increasing both vehicle downtime and charging requirements. Oversized

Figure 4 | **Total charge power installed (I) and charger utilization per day (II) as a function of battery size**



Source: Olsson et al. 2016.

battery packs provide a higher driving range per charge under optimal conditions but increase the curb weight, reducing the energy efficiency by 6–8 percent per ton increase in weight (Hodge et al. 2019), reducing payload capacity, and increasing vehicle cost. Moreover, the energy consumption of an e-bus largely depends on traction (route length, drive cycle, driver behavior, topography) and auxiliary power used for heating, ventilation, and air-conditioning (HVAC) system requirements during the trip, which must be considered when sizing a battery.

OEMs should decide on a battery size for a desired drive range and suitable charging requirements for different routes based on these factors. Overnight slow charging at the depot is economical, requiring minimum charging infrastructure. The usage of fast chargers for a large number of e-buses with small battery packs at the depot may strain the grid in future, due to the aggregated load, necessitating a shift towards an alternate charging strategy. Therefore, to maintain optimal SoC for travel, overnight slow charging is suitable for shorter routes. For longer routes and routes with higher power requirements, they can use a combination of overnight slow charging at the depot and opportunity charging (at a controlled C-rate) at the terminal to achieve a desired range.

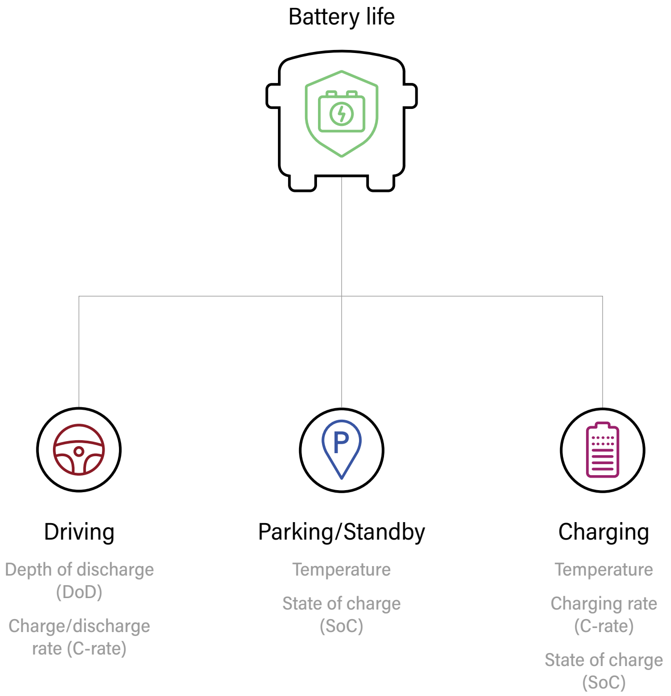
BATTERY LIFE IN E-BUSES

It is well established that EV battery life depends on various factors, such as battery chemistry, driving patterns, and ageing under the influence of different stress factors. This section, therefore, presents degradation trends for lithium battery variants under different stress conditions.

Factors affecting battery life

Batteries tend to age during the use phase of EVs as the irreversible physical and chemical changes occur due to environmental conditions, operational conditions, driving habits, and charging speed. Batteries degrade with time and usage, where the loss of capacity occurs during both standby (calendar ageing) and charging/discharging (cyclic ageing) conditions. Battery capacity fade and power fade are the two measurable quantities to assess battery degradation. Capacity fade, which means the decrease in charge storing capacity of a battery after every charging cycle, leads to EVs losing driving range capability over their lifetime. Power fade, which means a decrease in the amount of power a battery can provide due to an increase in internal resistance, results in a decrease in the performance of EVs, including acceleration, gradeability, and regenerative braking capabilities (Saxena et al. 2015). The battery life can be understood in three different yet coupled conditions as shown in Figure 5.

Figure 5 | **Different conditions affecting battery life**



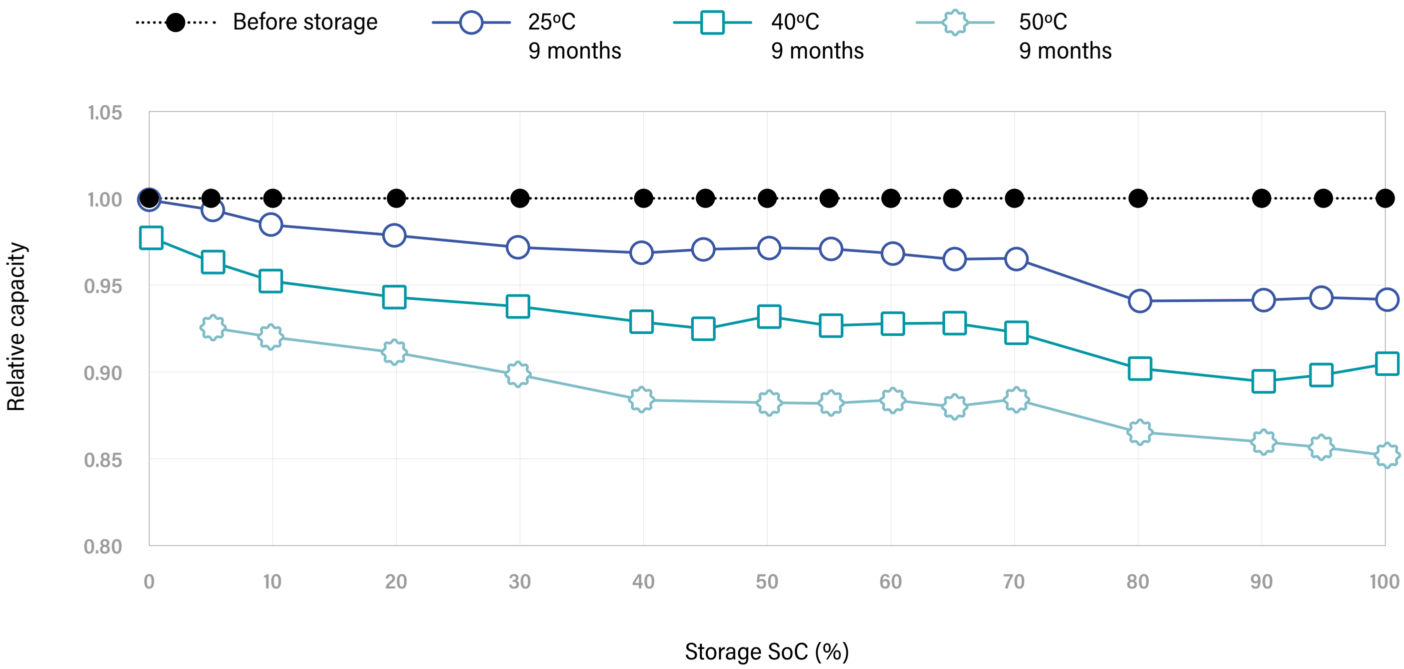
Calendar ageing

In a battery, calendar ageing occurs all the time but predominantly when the battery is idle, that is when the vehicle is parked and there is no flow of current through the LIBs (Beltran et al. 2022). The rate of battery degradation due to calendar ageing shows a very steady trend (Sui et al. 2021), wherein the rate of increase in capacity fade and internal resistance gradually subsides as the ageing advances.

Factors affecting calendar ageing

Factors such as state of charge (SoC) and battery temperature affect calendar ageing. From Figure 6 it is observed that a higher battery temperature along with high levels of SoC increases the rate of capacity loss. Here, the relative capacity is a measure of the battery capacity relative to its initial capacity. Comparing the effects of the two stress factors causing calendar ageing, it has been found that temperature has a more detrimental effect on the rate of degradation than SoC levels (Grolleau et al. 2014). In addition, the rate of degradation does not increase steadily with increasing SoC levels, as seen in Figure 6, that is the capacity loss remains almost the same for SoC levels, ranging between 40 and 70 percent (Keil et al. 2016).

Figure 6 | **Effect of temperature and SoC on LFP battery capacity (cell level)**



Source: Keil et al. 2016.

Cyclic ageing

The degradation occurring in batteries when they are being charged (during charging condition) or discharged (during EV usage) causes cyclic ageing. The rate of this degradation varies depending upon factors such as charge/discharge rates (C-rate), the temperature of the battery during usage, and the depth of discharge (DoD).

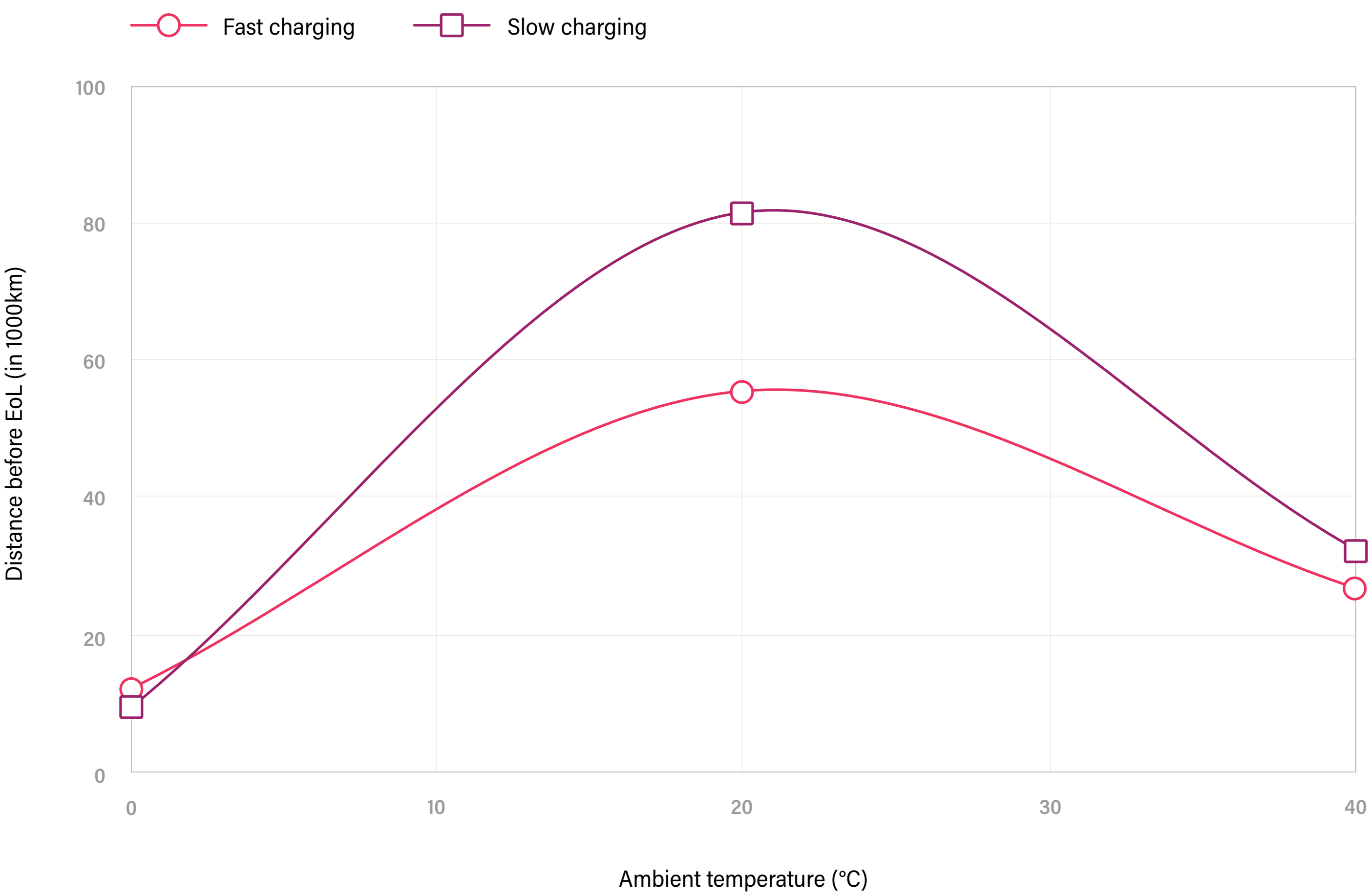
Factors affecting cyclic ageing during charging

During charging conditions, the rate of charging and temperature become key factors for cyclic degradation. Fast charging of the batteries (high C-rate) leads to higher rates of cyclic degradation. In NMC batteries, fast charging can reduce battery life by 10 percent (Bhagavathy et al. 2021). The impact of fast charging on the distance that the e-buses can travel before the battery`s end-of-life (EoL) is shown in Figure 7. The reduction in drivable distance before EoL is due to large capacity loss (a measure of high degradation) caused by fast charging. It's also observed that charging EV batteries at extreme temperatures accelerates cyclic degradation. Ouyang et al. (2016) observed that among the two stress factors mentioned, low temperature had a greater impact on cyclic ageing compared to high C-rates, as the uniformity of the battery deteriorates due to differences in temperature and voltage rates (Ouyang et al. 2019). In addition, although a battery with a higher SoC variation (0–100%) provides a higher drive range per charge in the short term than one charged to optimal SoC level, the degradation increases drastically with an increase in the range of SoC variation or over-discharge of the battery, as seen in Figure 8.

Factors affecting cyclic ageing during driving

According to a laboratory-accelerated ageing test, the internal temperature of the battery increases with a high rate of charge/discharge—caused due to driving speed and acceleration—leading to faster cyclic ageing of the battery

Figure 7 | **Effect of temperature and charging type on total drivable distance before end of life of an NMC battery (pack level)**



Source: Liu et al. 2020.

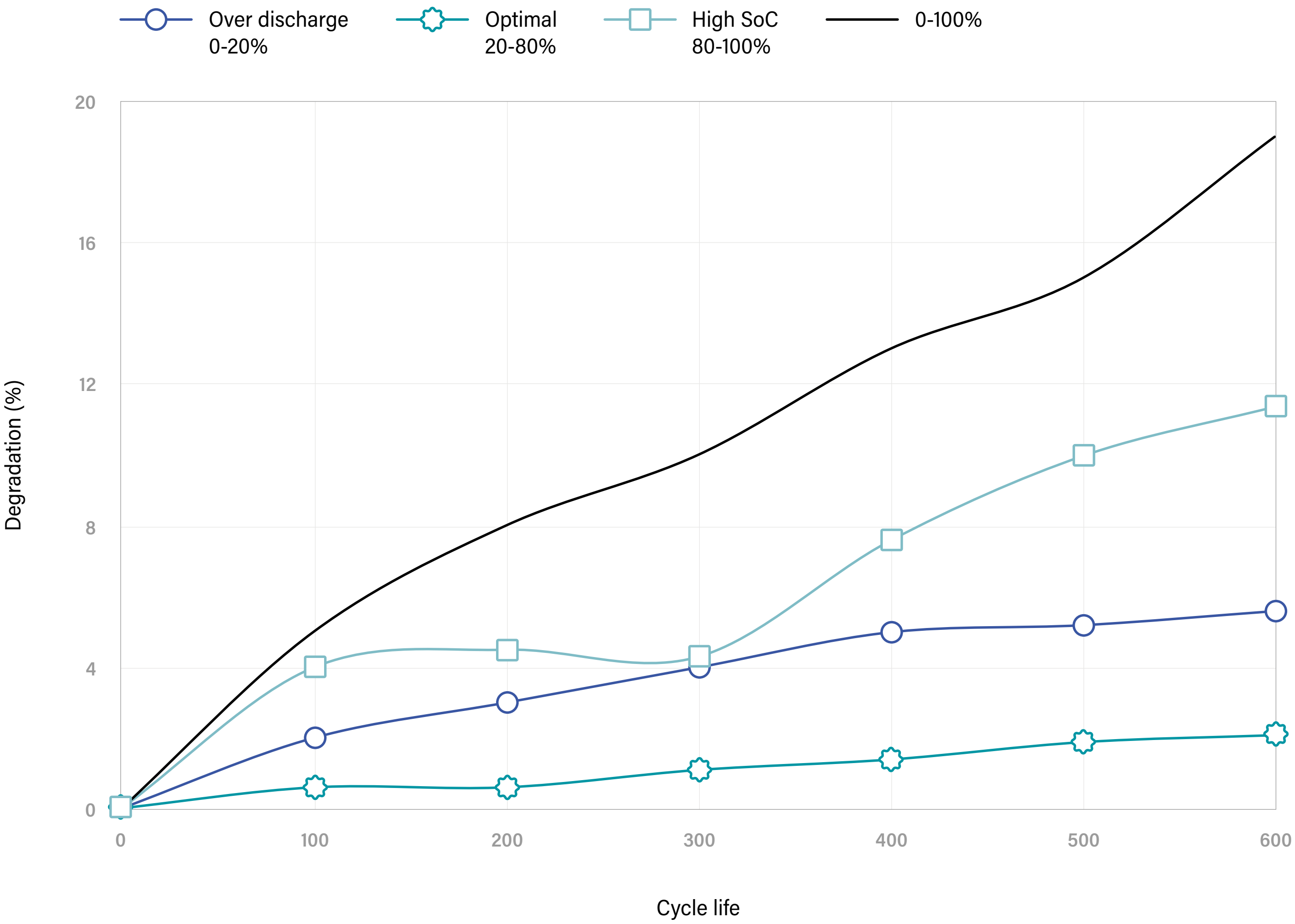
(Tomaszewska et al. 2019). In addition, over-discharging of the battery (high DoD) leads to an accelerated rate of degradation and capacity loss as shown in Figure 8. A regenerative braking system (RBS) is introduced to improve energy efficiency in e-buses, maintaining optimum SoC level, and avoiding deep DoD or frequent charging requirements. In contrast, high charging currents and longer duration of current flow due to RBS can lead to lithium plating, which increases ageing (Chidambaram et al. 2023). Therefore, the ratio of regenerative braking must be controlled to optimize benefits, increasing both energy efficiency and battery lifespan.

Battery life in a tropical environment

Lithium-ion battery variants are highly temperature sensitive, which means the degree of variability between the ambient and the ideal operating temperature of the battery plays a major role in the total rate of degradation. Figure 9 shows the effect of temperature on battery life. The cycle life of LFP batteries, as observed by Chinese e-bus manufacturers Yutong group, falls drastically with increasing temperature; that is it takes 4,000 cycles for the battery to reach its end of first life at 25°C while only around 2,000 cycles to reach end of first life (i.e., 80 percent capacity) at 45°C. In an NMC battery, the number of cycles before the end of the first life decreases from 1,200 cycles at a temperature of 34°C to 500 cycles at 46°C (C40 Cities 2021).

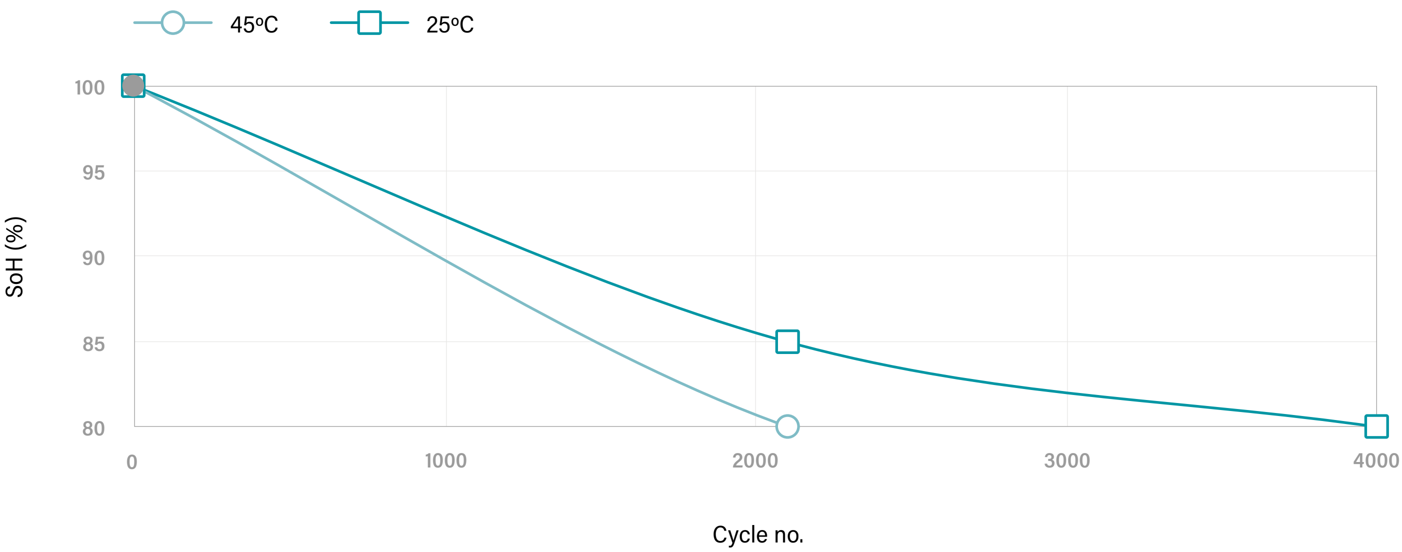
Batteries in EVs have a risk of high degradation in operational conditions like higher temperatures, dynamic loads, and overcharging and discharging patterns, posing concerns about battery life and safety. These factors in a tropical region generate a large amount of heat in a battery with up to 10°C variations between the core and surface levels, triggering battery ageing and thermal runaway (Samanta and Williamson 2021). Recent evidences suggest that such uncontrollable thermal runaways can lead to EV batteries catching fire (Shah 2022). To regulate the temperature within the optimal range

Figure 8 | **Battery life of an LFP variant at different SoC windows (pack level)**



Source: Jiang et al. 2013

Figure 9 | **Effect of temperature on LFP battery life (pack level)**

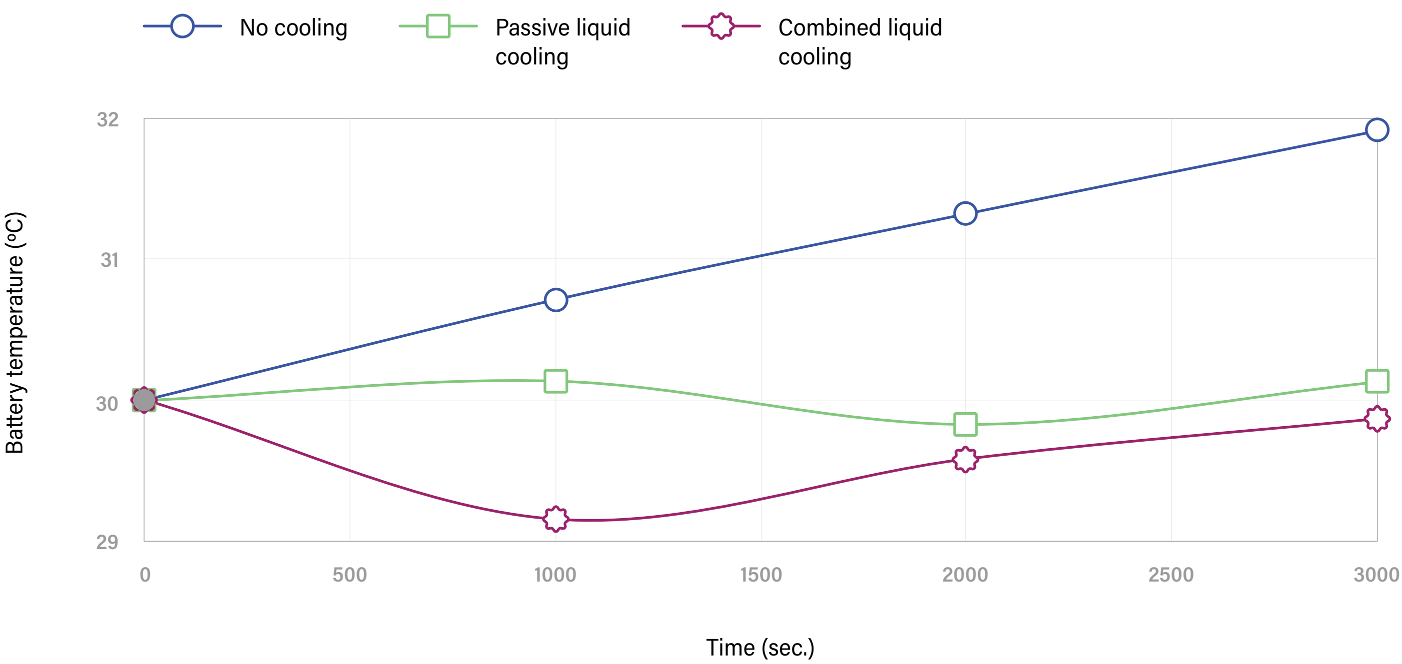


Source: Yutong n.d.

of 15–35°C, (Ma et al. 2018) an efficient battery thermal management system (BTMS) that operates on the commands of the battery management system (BMS) is required for either heating or cooling the battery, which is important for increasing the lifetime of a battery.

Among the various BTMSs, a combined liquid cooling system is more suitable for tropical regions to control the battery temperature, as shown in Figure 10 (Bhatia 2020). It utilizes active as well as passive cooling systems to maintain the optimal battery temperature under extreme conditions with minimum energy consumed (Li and Zhu 2014). Piao et al.

Figure 10 | **Comparison of different types of battery thermal management systems**



Source: Piao et al. 2020.

(2020) revealed that combined liquid cooling saved twice the amount of energy against using only active cooling and maintained the battery's temperature under desired range. Despite reduced battery degradation, the BTMS requires technological innovation to contain space consumption, increase in EV weight, and reduction in battery pack energy (Wankhede et al. 2022). It is noteworthy that though the BTMS can increase the battery pack costs by 3–7 percent, it decreases the life cycle costs by 27 percent (Lander et al. 2021).

Battery degradation trends in different LIB variants

The thermolabile nature of batteries can be understood by assessing the pack-level behavior of different battery variants under different scenarios. Taking inspiration from available data on the LMO variant, we assessed the contribution of calendar and cyclic ageing in battery degradation. We also studied real-world and extrapolated data to infer degradation trends of LFP, NMC, and LTO batteries. Later in this section, we examine the life of these battery variants being operated in the same external conditions to understand their suitability—best to worst—in e-buses.

LMO battery pack

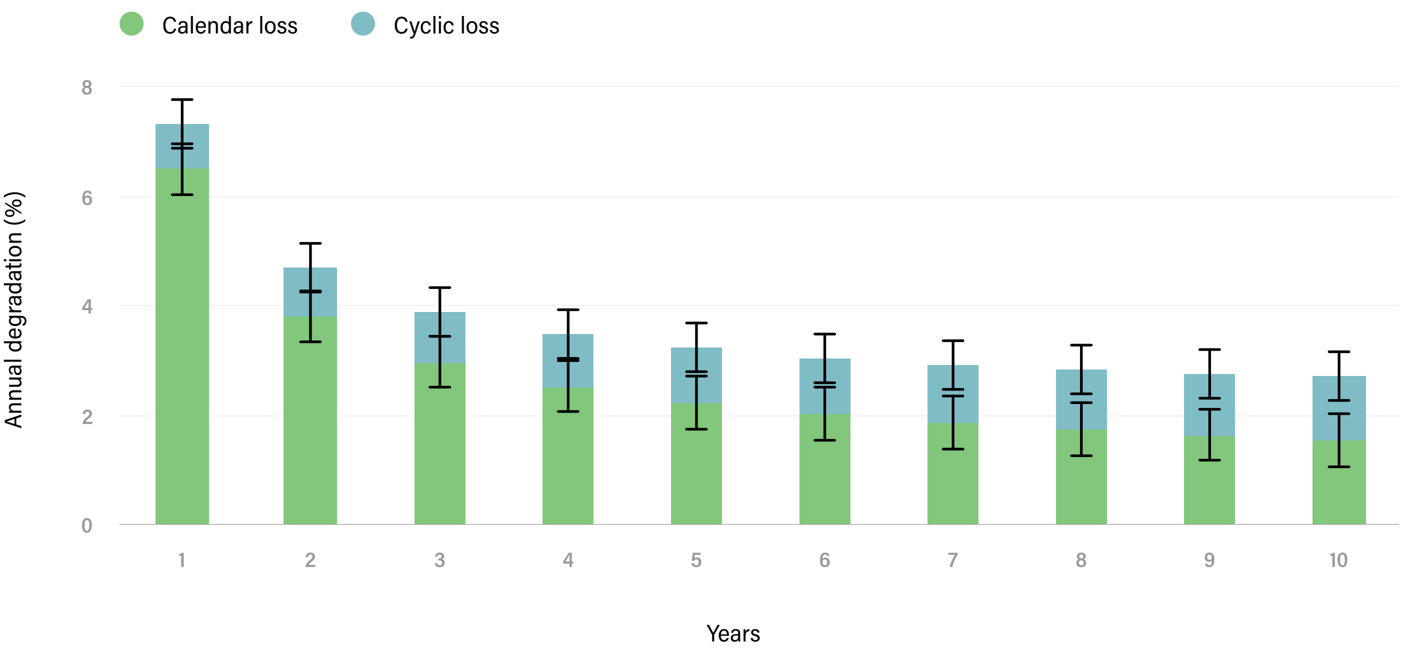
A case study by Yang et al. (2018) presents the trend of annual battery capacity loss of the LMO battery variant in real-world operating scenarios. The study highlights that the degradation due to calendar ageing is dominant in the first year and keeps reducing over time whereas degradation due to cyclic ageing reduces marginally through the life of the battery (seen in Figure 11). The degradation trend followed by calendar ageing is due to the formation of a solid electrolyte interphase (SEI) layer (SEI layer is formed due to an electrochemical reaction between the electrode and the electrolyte), which initially causes high capacity fading but protects the electrodes from faster degradation in the later stages, reducing the share of calendar ageing in the subsequent years (Molaeimanesh et al. 2021).

Another study by Yang et al. (2018) presents the year-wise degradation of an e-car battery due to both cyclic and calendar ageing in different states of the USA. The study concludes that calendar ageing in a low-temperature region like Alaska is just 18.02 percent over 10 years, whereas in a high-temperature state like Hawaii, it is 39 percent. This shows that there's a correlation between ambient temperature and the rate of calendar ageing in LMO batteries.

LFP battery pack

The degradation trend of an LFP battery variant can be understood by analyzing e-buses deployed in China, as shown in Figure 12. These battery packs operate in different geographical regions with varying temperature conditions. It can be observed that in an e-bus operating in Zhengzhou where the average ambient temperature ranges between 0 and 30°C,

Figure 11 | **Annual battery capacity loss of an LMO battery pack in the USA**



Source: Yang et al. 2018.

the battery pack reaches its end of life within approximately 900 cycles or 2.5 years (Li et al. 2020, Applied Energy), falling short compared to the life claimed by the manufacturers. On the contrary, in the e-buses operating in Shenzhen where the average temperature ranges between 15 and 30°C (battery optimal temperature) (Climates to Travel 2022), batteries have an average life of five years (Li et al. 2020, ACM Digital Library), inferring that lower ambient temperature than the operable range has a large impact on LFP battery degradation. Cyclic ageing is one of the key reasons for such degradation at lower temperatures.

NMC and LTO battery packs

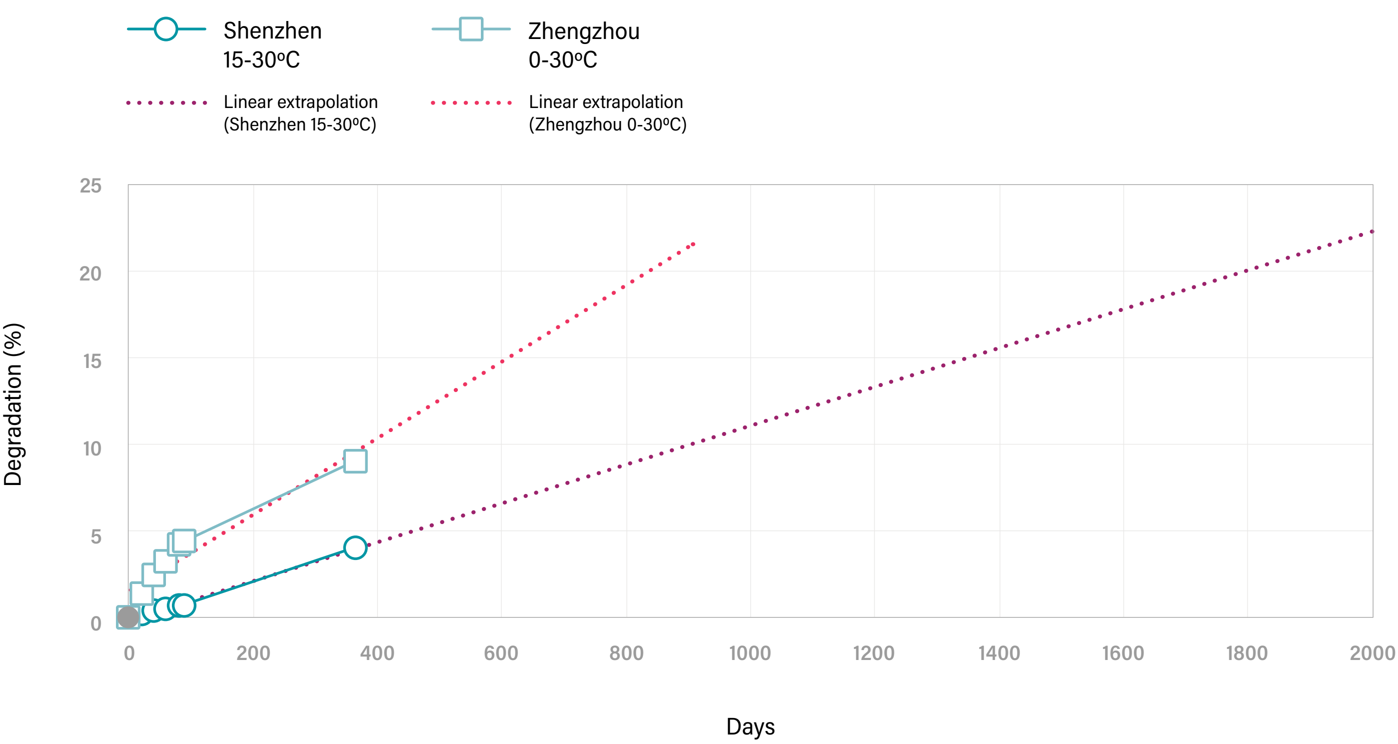
A 310 kWh NMC battery pack and a 90 kWh LTO battery pack by battery manufacturer BMZ, Poland, were analyzed and the rate of degradation was compared in both the variants (Sustainable Bus 2021 A). It is observed that the NMC battery pack reaches 80 percent of its capacity in around eight years compared to the LTO battery pack which lasts beyond 10 years, indicating that the LTO variant has comparatively higher battery life. In addition, from Figure 13 it can be observed that like other LIB variants, the degradation rate is highest in the initial years of the automotive life of NMC and LTO batteries.

While the obtained degradation curves may help in developing battery life models, one cannot compare the battery life of these three variants solely on the degradation curves as these battery packs have been used under dissimilar stress conditions that were not disclosed by the manufacturer.

Comparison of LIB variants under the same conditions

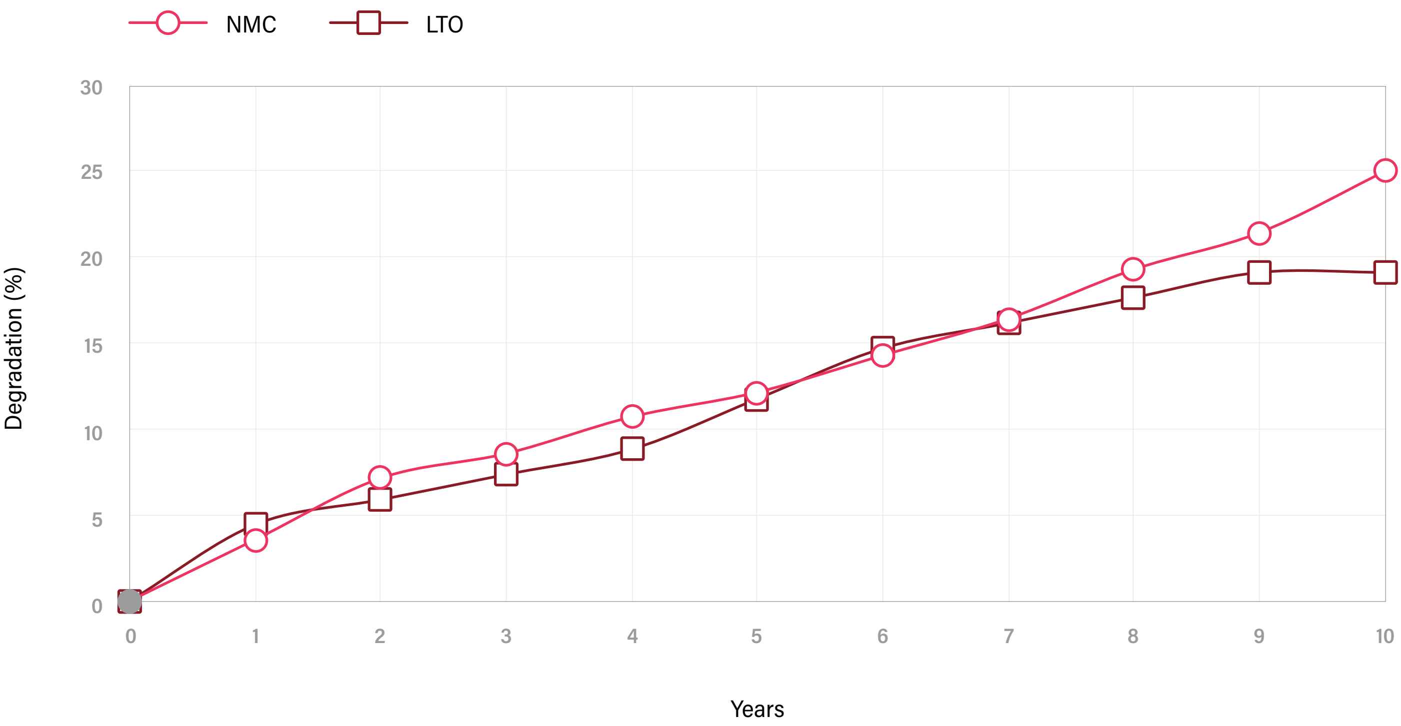
Operational data under similar conditions are needed for comparing different battery chemistries. A case study was carried out by Al-Saadi et al. (2022) in Europe, based on a simulation of real driving cycles of e-buses with LFP, NMC, and LTO battery variants used in three European cities. Three cities with different temperatures, charging frequencies, and load demands were considered for analyzing and comparing the rate of degradation in these variants. In addition, the study also highlights the stress factor causing the highest degradation. The three cities with their specific conditions are given in Table 6.

Figure 12 | **Battery degradation trend of LFP battery pack in e-buses**



Source: Li et al. 2020 (*Applied Energy*); Li et al. 2020 (*ACM Digital Library*).

Figure 13 | **Comparison of battery degradation trends of NMC and LTO battery packs**



Source: Sustainable Bus 2021 A.

Table 6 | **Different study conditions for analyzing battery behavior**

SPECIFICATION	BARCELONA (BCN) SCENARIO A	OSNABRUCK (OSN) SCENARIO B	GOTHENBURG (GOT) SCENARIO C
Bus line	L33	N5	R55
Average operational trip distance/day (km)	155	195	167
Maximum/Minimum temperature (°C)	29/9	23/0	22/-2
Characteristics	Low demand Low charging frequency Warm climate	High demand Medium charging frequency Cool climate	High demand High charging frequency Cool climate

Source: Al-Saadi et al. 2022.

The degradation rate obtained after the first year for different battery variants operating under the above-mentioned conditions and varying C-rates is shown in Table 7.

From Table 7, the following observations are made:

- NMC batteries suffer the highest degradation in scenario A where the batteries are deep discharged to utilize low charging frequency, implying that NMC batteries are the most sensitive to DoD. Therefore, an NMC battery pack should be operated at a lower DoD than a comparable LFP.
- Compared to other chemistries, C-rate contributes more to the degradation of NMC variants. For instance, a 2.25 times increase in the degradation rate of NMCs is observed in scenario A while the change is negligible in the LFP and LTO variants.
- Under moderate temperatures, reduction in DoD due to the introduction of en-route charging (high frequency charging) improved battery life. This can be seen in scenario C, which experiences frequent charging requirements.

Table 7 | **Degradation results of different lithium-ion battery variants with varying C-rates**

SCENARIOS	1C			2C			3C		
	Degradation after 1-year (%)								
	LFP	NMC	LTO	LFP	NMC	LTO	LFP	NMC	LTO
Scenario A	2.76	4.00	1.00	2.76	6.59	1.10	2.76	9.00	1.20
Scenario B	2.97	5.10	1.10	2.97	6.30	1.20	2.97	7.90	1.30
Scenario C	2.49	4.90	0.98	2.49	5.49	1.00	2.50	6.50	1.1

Source: Al-Saadi et al. 2022.

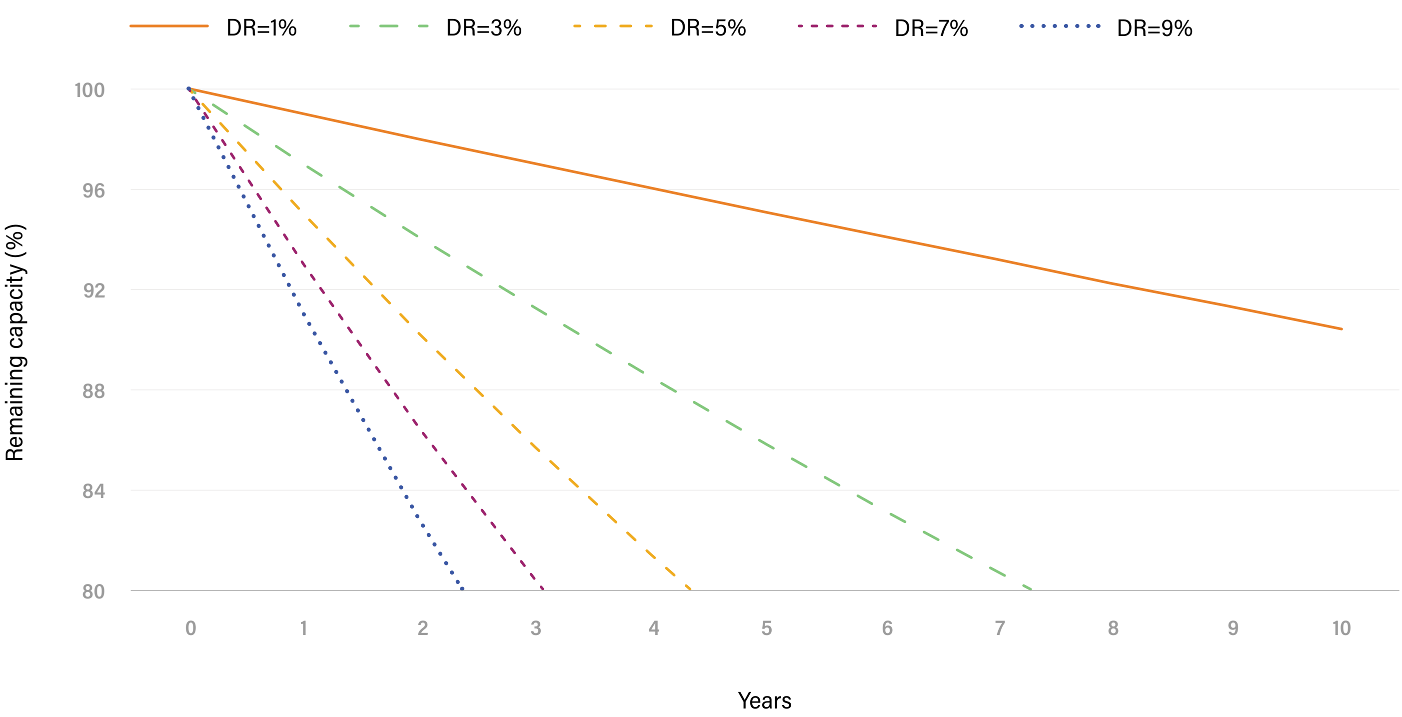
- Under the given scenarios, LTO batteries lasted the longest before reaching its EoL, followed by the LFP, with NMC batteries having the shortest lifespan.

In e-buses, once the batteries degrade by 20 percent of their initial capacity and have more than 5 percent self-discharge over 24 hours, they are no longer suitable for automotive applications. Given that batteries degrade over their lifespan, it is imperative to find out the degradation rate under which the ideal battery life can be achieved. Figure 14 shows the life of a battery at different average annual battery degradation rates. The trend suggests that approximately seven years of battery life can be achieved at an average of 3 percent annual degradation rate, whereas a 9 percent average annual degradation rate can limit the battery life to less than three years. Having established that the degradation rate is highly susceptible to external factors, it is important to limit the battery's exposure to them to achieve optimum battery life for e-bus applications.

Key observations for Indian operating conditions

As discussed, India experiences varied climatic conditions ranging from a hot tropical climate to cold and sub-zero temperatures. In order to limit the average annual degradation rate to less than 3 percent, factors contributing to degradation in a particular region must be identified and best practices

Figure 14 | **Battery life in e-bus application at 80% SoH at different degradation rates**



Source: Authors' analysis.

must be implemented to maintain good battery health. Calendar ageing will be more dominant in regions with higher ambient temperatures, especially in the e-buses running at a higher SoC. Since temperature is a major stress factor for the degradation of batteries in tropical regions, a combined liquid cooling BTMS must be installed to maintain the optimal battery temperature range. In regions with ambient temperatures lower than optimum, cyclic ageing will cause lithium plating and loss in lithium inventory, leading to battery degradation (Lander et al. 2021). Wrapping the batteries with insulation material will help batteries warm up faster, reducing battery degradation at lower temperatures. Cyclic ageing is further triggered by high charging rates, high DoD (100 to 0 percent), and extreme operating temperatures. Degradation due to calendar ageing after the initial years of EV operation reduces substantially for batteries due to the formation of a protective SEI layer, whereas degradation due to cyclic ageing sees only a slight reduction over the years.

LFP and NMC variants are the popular batteries for EV applications in India. Degradation in the LFP variants is temperature driven to an extent while degradation in NMC batteries is highly impacted by C-rate. Compared to LFP, NMC variants under the same operating conditions degrade faster when operated at higher DoD, higher temperatures, and high C-rates. While LFP variants are suitable for shorter distances with opportunity charging facilities, NMCs are suitable for longer distances with overnight slow charging.

IMPACT OF HIGH BATTERY DEGRADATION

This section discusses the impact of degradation on operational factors such as battery sizing and range estimation, operational efficiency, and replacement ratio, and how it affects economic viability and sustainability of e-bus business models.

Short-term impact of battery degradation

The usage of an e-bus battery under non-optimal conditions of temperature, SoC, DoD, and charge/discharge rate (C-rate) leads to fast degradation in the original capacity of e-buses, affecting the planned operational schedule of an e-bus. High battery degradation will have an immediate impact on the following components:

Battery sizing and range estimation

A bus operator selects an e-bus technical specification, including battery capacity, based on the route requirement and charging strategy. For instance, an e-bus operator would choose a large battery size with an overnight charging strategy that is adequate to cover the planned trip over a small battery pack to cover the same route. Adequate range estimation can be hindered by higher degradation as it leads to reduction in the battery capacity, which makes it inadequate to complete the planned trip.

The usable capacity of an e-bus is set at 70–80 percent of the nameplate capacity to avoid degradation due to aggressive DoD. The energy consumption of an e-bus, as quoted by Indian OEMs, ranges between 0.8 and 2 kWh/km (Das et al. 2019). It must be noted that these values can change in regions with high and low temperature extremes due to the change in auxiliary power requirements for air-conditioning, heating, etc. Due to the variation in mileage, the operational range per charge changes compared to scheduled trip distance. Additionally, as the battery capacity fades due to accelerated degradation, driving range per charge is further reduced, requiring an additional number of charging cycles to finish a day's trip. This was observed in a study done by McGrath et al. (2022) that concluded that the e-bus drive range per charge decreased by 26 percent during its automotive life due to accelerated capacity fade. The study also concluded that the energy required to cover the same route increased by 7 percent, suggesting a decline in energy efficiency. Under such conditions, along with the increased charging requirements, the batteries may require replacement long before the ideal time, which will further worsen the economic viability of the e-buses.

Operational efficiency (city level)

E-buses with high battery degradation become less serviceable due to increased charging requirements. This has a major impact on the operational efficiency of the fleet. Moreover, routes with lower passenger movement don't have backup vehicles deployed. Therefore any reduction in the range or high energy demand due to high battery degradation will lead to the unavailability of buses, directly impacting the e-bus scheduling process for a given route.

Replacement ratio of conventional buses to e-buses (route level)

Replacement ratio in this context refers to the share of e-buses required to obtain the same fleet operational efficiency as that of a diesel bus fleet. Cities must be able to achieve a replacement ratio close to 1:1 for better economic viability of e-bus fleets. The replacement ratio is based on the operational efficiency of e-buses, which is influenced by battery size, drive range estimation, and charging strategy (Xue et al. 2019). As established, high battery degradation impacts these factors, requiring the deployment of more e-buses by the operator than the replacement ratio set while planning the fleet electrification. Apart from controlling the degradation rate in batteries, the San Tiago model for improvement in operational efficiency can be explored for achieving 1:1 replacement ratio. The city improved its operational efficiency by identifying the right charging strategy, which included adoption of faster combined charging systems (CCSs) and development of e-bus corridors with bus-terminal charging facilities, in addition to taking city-specific technical specification of range, charging speed, and vehicle downtime into consideration (Jin 2020; Allan et al. 2021).

Long-term impact of battery degradation

The long-term impact of battery degradation is directly linked to the economic viability and sustainability of the e-bus business model discussed below:

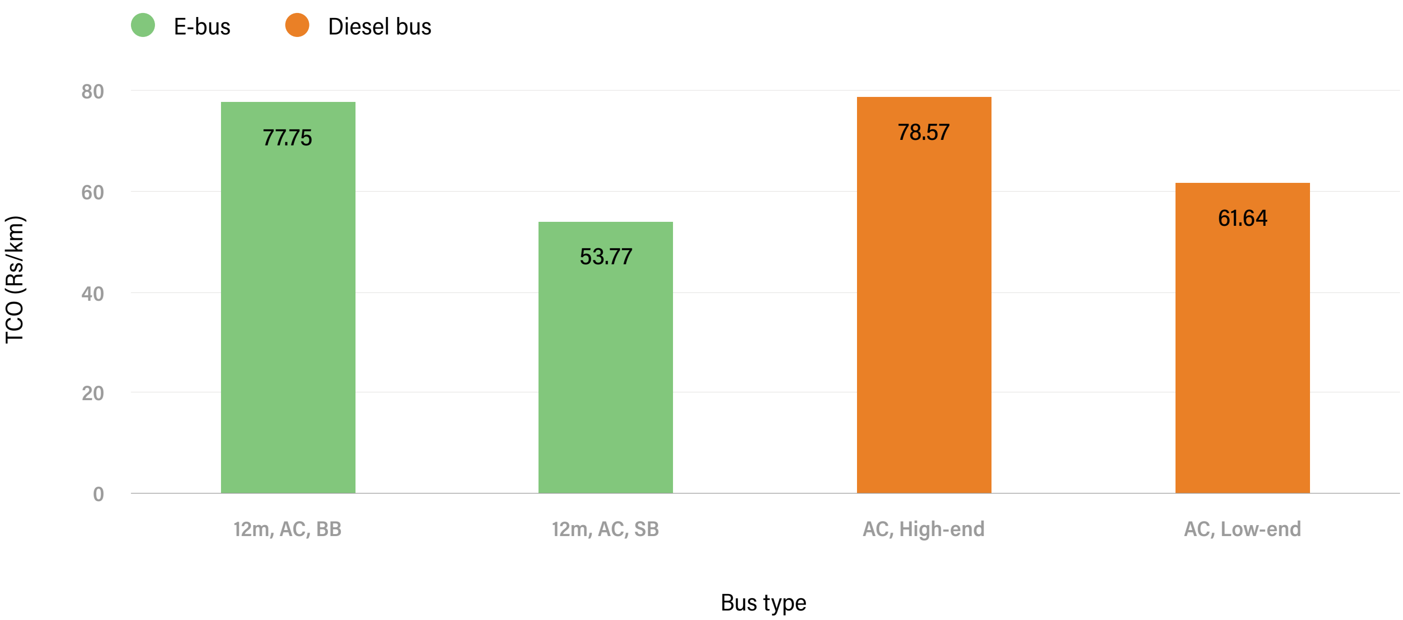
Economic viability of the e-buses

A financial analysis is of key importance to determine future savings and enable the e-bus fleet managers to understand the return on investment despite higher upfront costs compared to that of conventional buses (Johnson et al. 2020). The TCO analysis is one of the methods to assess the financial viability of e-buses. On determining the TCO per km, fleet managers will be able to analyze the net earnings per km by transitioning to e-buses.

Figure 15 shows that the TCO per km of a 12 meter AC e-bus with a big battery pack (12 m_AC_BB) is less than the high-cost diesel counterpart but higher than the low-cost diesel variant for the average daily travel distance of 200 km. With nearly a 40 percent reduction in the battery pack size (320 kWh to 125 kWh), the TCO per km of 12 meter AC e-bus with a small battery pack (12m_AC_SB) becomes even less than the low-cost diesel variant, showing the impact of battery cost on the economic viability of e-buses. Higher degradation rates can lead to the battery reaching its end of first life faster, causing frequent battery replacements to meet operational efficiency.

Another study carried out by MOBI Electromobility Research Centre, Brussels, compared the impact of the reduced battery life of public e-bus on the TCO for 10 years. They concluded that as the battery lifespan reduced by 40 percent, the TCO of the e-bus increased by 4.3 percent, compared to the TCO for rated capacity of the e-bus battery. Moreover, the impact of degradation on TCO of e-buses using depot charging strategy was found to be higher than those using opportunity charging. (Nils et al. 2019). The increase in TCO due to high degradation (reduced battery lifetime) impacts the economic viability and the sustainability of the e-bus business model.

Figure 15 | **Effect of battery size on TCO per km**



Source: Kumar and Chakrabarty 2020.

Operational cost

At the route level, fuel efficiency and the distance traveled per day largely impact the TCO per km of an e-bus. A case study carried out by Nurhadi et al. (2014) on a public e-bus in Sweden concluded that the TCO increased by 13–30 percent as the driving range of the e-bus decreased by 10–30 percent. Moreover, higher degradation impacted the operational efficiency at the route level, incurring additional costs to purchase more buses to meet the operational efficiency of the diesel bus counterpart.

Zhang et al. (2022) observed that considering only charging costs resulted in an unsustainable charging strategy solution, as the e-bus operator would wait for the time when the cost of charging is lower in the power supply grids. This resulted in e-buses reaching very low levels of SoC (high DoD), leading to high wear costs (due to high degradation) and frequent battery replacement. Ineffective charging scheduling increases battery wear, further increasing the operational cost of e-buses by 21.79 percent, compared to the case where an optimal charging strategy was adopted to reduce battery wear cost. From the above observations, it can be concluded that battery wear cost is an integral part of the operational cost of the e-buses and thereby the economic viability of e-buses. For e-buses having big battery packs with high flexibility for overnight charging (depot charging) durations, the combined consideration of charging costs and battery wear costs provide enhanced outcomes. The cost of battery replacement and the affected operational cost (city and route level) due to the immediate impact of battery degradation will affect the sustainability of the business model in the long run, making it difficult for fleet owners to hit the break-even point.

SUMMARY AND WAY FORWARD

The battery life of an e-bus plays a significant role in its performance, economic viability, and sustainability of the business model. Batteries undergo degradation due to calendar and cyclic ageing which is accelerated by various operating conditions like temperature extremes, high charge rate and DoD, and load demands. In order to obtain an optimal battery life in e-buses, the following selected recommendations are proposed:

Operational recommendations

State of charge and temperature management

To reduce degradation during standby/parking or storage conditions: Calendar ageing in batteries is accelerated at high SoC levels (>50 percent) and elevated temperatures (beyond 35°C). Hence, fully charged e-buses should not be parked for a long time in high-temperature conditions. Parking charged e-buses under shade during long halts can help keep the battery temperature close to optimum conditions. Moreover, while storing charged batteries, exposure to sunlight and extreme temperature fluctuations must be avoided.

Charging and discharging strategy

To reduce battery ageing during driving conditions: Cyclic ageing during operation is accelerated by deep DoD and temperature extremes. Ensuring partial discharge of the battery during operation, which is around the SoC range of 20–80 percent, and the lowest average SoC can reduce the rate of cyclic ageing. Factors such as aggressive driving and high payload capacity accelerate cyclic ageing, wearing out the batteries faster, and hence must be avoided.

Reducing ageing during charging conditions: An e-bus battery should always be charged at the optimum temperature range (15–30°C) to avoid cyclic ageing. Prolonged charging at lower temperatures leads to high heat generation, increasing battery degradation. Therefore, batteries should be charged at a lower C-rate for lower temperature conditions (0–15°C), and below-freezing point charging should be avoided for enhanced battery life.

As cyclic losses almost double when the battery is overcharged (beyond 80 percent SoC), the e-bus should be charged between 20 and 80 percent SoC. Moreover, frequent direct current (DC) fast charging generates more heat than slow charging, increasing battery wear and tear. Avoiding frequent DC fast charging preserves the battery life by 10 percent. Depot charging combined with opportunity charging is recommended for e-buses operating for longer distances, as it helps avoid cycling of batteries outside optimal SoC and DoD levels, thus reducing the rate of cyclic degradation.

Planning recommendations

Battery sizing and charging strategy: The battery must be sized for a required average daily driving distance on a single charge, considering the specific energy consumption (estimated) of the bus route of the city of operation. To avoid oversizing of battery pack for meeting the route requirement, overnight depot charging and optimal scheduling can be adopted for short distances (e.g., 150 km/day). Overnight charging with opportunity charging (at the terminal) can be adopted for longer distances to ensure the smallest SoC variation or low average SoC level of battery packs.

Degradation and opportunity charging cost in TCO estimation: Battery wear costs and opportunity charging costs must be considered instead of charging cost alone when determining an ideal and financially sound charging strategy.

Circular economy in e-bus business models: E-bus batteries are unfit for automotive use after losing 20 percent of their initial capacity but have sufficient capacity for other energy storage applications. OEMs should improve data collection for precise residual value calculation of these batteries to identify their fitness for various second-life applications. Refurbishing and recycling of the retired batteries will not only improve the environmental impact of the batteries but will also add a revenue stream to the business model, reducing the TCO per km of e-buses.

Driver training: EVs have limited driving range, where aggressive driving accelerates energy consumption. An increase in top-up (fast) charging requirements to finish the desired trips by e-bus due to high energy demand can increase battery capacity fade and charging costs. Intelligent fleet monitoring and optimal driver behavior during operation can play a critical role in promoting economical driving.

Given e-buses are relatively new technology for drivers, OEMs must give systematic training to build the drivers' knowledge about e-buses and their components. Moreover, eco-driving trainings have proved to improve energy efficiency, maintain battery health, and reduce opex. With respect to the route drive cycle, bus operators can build training modules on optimal management of speed, acceleration, deceleration, use of regenerative brakes, and charging en-route and at the depot. Drivers must also be trained in maintaining the optimal SoC during standby and charging, DoD during operation, and charge with desired C-rate to avoid loss of cycle life of batteries.

Technical recommendations

Efficient BMS and TMS for battery: Given the high impact of non-optimal temperature on battery life, e-bus battery packs must be equipped with the intelligent BMS. This will help monitor and protect cells and battery pack. Intelligent BMS will help minimize safety concerns and will help monitor and record the change in the battery health (i.e., SoH) of the battery due to various external factors.

In regions that experience high temperatures, a combined cooling liquid battery thermal management system (BTMS) must be adopted to maintain battery temperature in the optimal range (i.e., 15–35°C) to reduce battery degradation. In low-temperature regions, the use of insulation material (IM) can help in warming up the batteries with a reduced decay rate and improve the discharging performance. This can help in achieving lower cell and pack-level degradation. Optimization at the cell design level to promote better heat dissipation and thermal management can reduce battery degradation, which could extend the battery life, and hence reduce battery wear costs.

Regenerative braking system adoption: In an e-bus, efficient utilization of the regenerative braking system (RBS) can be one of the solutions to manage the uncertainty in the energy consumption per km due to varying operating conditions. RBS in an e-bus, especially in congested cities with frequent braking requirements, can help recharge the battery using kinetic energy generated during deceleration. It is to be noted that regenerative braking alone cannot bring down a speeding vehicle to zero speed. Therefore, it should be coupled with friction brakes to bring the vehicle to zero speed. RBS must be designed to minimize battery capacity loss due to cyclic ageing under the high rate of current delivered to the battery by regenerative braking.

Technical performance and efficiency: In e-buses, auxiliary requirements account for almost 50 percent of the total energy consumption per km and contribute significantly to the uncertainty of the energy consumption per km due to variations in the local operating conditions. To optimize energy usage for auxiliary requirements, the e-bus must be equipped with an intelligent energy management system to monitor and regulate energy demands with changing temperatures. Also, an energy-efficient heating, ventilation, and air-conditioning (HVAC) system must be used in e-buses.

E-buses must be equipped with an eco-driving assistance system (EDAS), which can help to extend the range up to 30 percent by efficient energy utilization. Along with the regenerative braking system (RBS), e-buses should adopt a smart control strategy for the efficient utilization of the recovered energy. Improving energy efficiency will help avoid high DoD during trips, reducing the need for top-up charging and reducing battery degradation.

Policy recommendations

Battery data collection and management: A major limitation for developing various battery ageing management strategies is the unavailability of region-specific, pack-level, real-world operational data on e-bus batteries. Different regions have different temperature conditions, driving behaviors, and other external conditions, which can affect battery life differently. Region-specific multi-stakeholder partnerships need to be developed for gathering and transferring real-world data.

To overcome the data gap in India, e-bus OEMs and operators need to develop a mechanism for collecting and securely sharing real-time data for analysis, in order to identify region-specific battery issues. Annex B suggests a template for data collection, where the data collection frequency can be fixed based on the trade-off between cost and benefit analysis of data collection and management. Some of the possible analysis and its benefits are listed below:

- **Battery life assessment:** The availability of data will improve understanding of the various battery health indicators for different chemistries during their automotive lifetime. This will help in assessing the role of various external stress factors in catalyzing degradation by both calendar ageing and cyclic ageing in different battery chemistries.
- **Efficient planning for operation:** A better understanding of battery life can lead to the development of best operating practices and innovative solutions to minimize battery degradation in various operating situations.
- **Technology development:** An understanding of region-specific factors of e-bus battery degradation, which can foster technical innovation such as best-suited temperature controllers for maintaining the health of different battery packs.
- **Residual value and second life:** Availability of data about cell and pack health will help estimate precisely the end-of-life residual value of the e-bus battery. This will play a crucial role in estimating the intrinsic value of the battery and its suitability for either second life application or EoL recycling.

Standards, regulation, and testing: With the availability of region-specific data on major factors affecting battery degradation, fit-for-purpose standards can be introduced in place of current battery standards. For example, in batteries manufactured for e-buses operating in India, the fit-for-purpose standards will match the environmental conditions (temperature, humidity) and abuse conditions (aggressive C-rates, DoD, physical damage), and actual operating circumstances in the country.

Battery durability testing under these standards can precisely estimate battery ageing and impact on cycle-life of the e-bus batteries in specific regions. Durability testing will yield further data on possible battery-related accidents, helping manufacturers take adequate safety measures.

ANNEX A. BASIC TECHNICAL DETAILS

List of key performance indicators (KPIs)

- **Battery capacity (Ampere.hour):** The total amount of electricity produced from the electrochemical reactions that occur inside a battery throughout its lifetime determine its total capacity.
- **Specific energy density (kWh/kg):** It is the amount of energy a battery contains per kilogram of its weight.
- **Charge/discharge rate (C-rate):** It refers to the rate at which current is being drawn from or to the battery, whereas the depth of discharge refers to the extent to which a fully charged battery is being discharged.
- **Cycle life:** Cycle life is the number of full charge and discharge cycles a battery can go through before dropping to 80 percent state of health (SoH).
- **Driving range:** Driving range depicts the distance an e-bus can drive per charge cycle.
- **Operable temperature range:** It is the range of ambient temperature in which a battery can operate optimally.

Factors affecting battery degradation

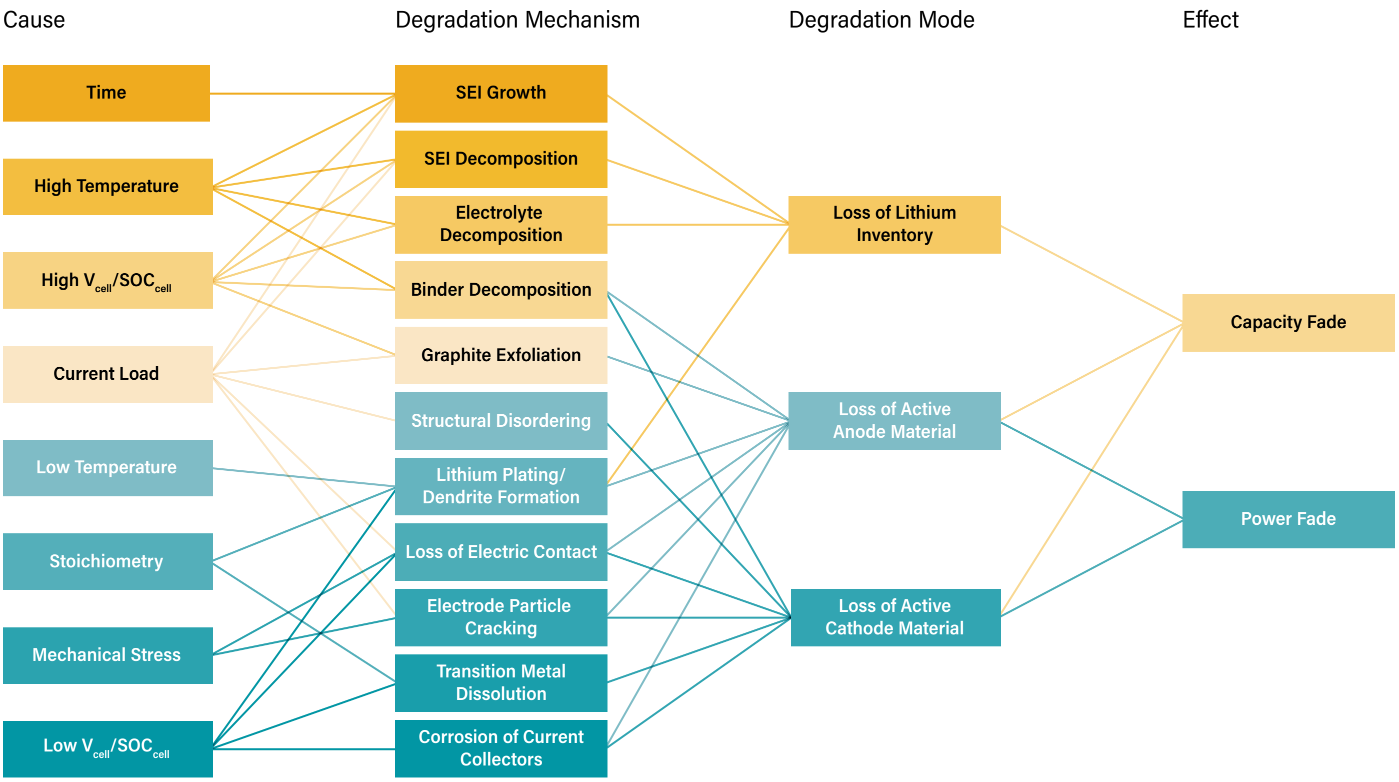
External factors play a major role in battery degradation as they lead to various side reactions (degradation mechanisms) resulting in either of the three degradation modes leading to quantifiable effects on battery in terms of either capacity or power fade as shown in Figure A1.

Causes of degradation

Temperature: High temperature results in thermal decomposition of the electrode and the electrolyte, leading to increase in thickness of SEI film on the anode. This results in an increase in consumption of lithium ions, leading to capacity fade. A study by Xiong (2019) suggests that 25°C increase in temperature from 0–25°C resulted in just 2 percent capacity fade, whereas increase in temperature from 25–40 °C resulted in an additional 10 percent capacity fade. Lower temperature results in side reaction due to lithium deposition, resulting in capacity fade and safety concerns (Xiong 2019).

State of charge (SoC): High SoC levels lead to an increase in the open circuit voltage, resulting in lower anode potential and higher cathode potential. Lower anode potential here leads to an

Figure A1 | **Effect of factors leading to battery degradation**



Source: Birkl et al. 2017.

increase in SEI growth and electrolytic oxidation, thereby resulting in a capacity fade. However, a very low SoC level also results in an increase in capacity fade and internal resistance of the cell, leading to power fade (Xiong 2019).

Depth of discharge (DoD): Higher DoD or a deep discharge (DoD>50 percent) damages the negative electrode site, and the electrodes start to undergo phase change, resulting in structural and volume change. This then results in capacity loss (Xiong 2019).

Charge/discharge rate (C-rate): High charge voltages increase the battery runtime while resulting in lithium plating and loss of lithium due to formation of metallic lithium on the anode. This causes capacity loss with a greater risk of fire within the cell due to internal short circuiting (Xiong 2019).

Degradation modes

Loss of lithium-ion inventory: Parasitic reactions such as SEI growth, decomposition reaction such as SEI and electrolyte decomposition, and lithium plating may lead to the unavailability of lithium ions cycling between the electrodes, resulting in a capacity fade (Birkl et al. 2017).

Loss of active material of anode: This mode of degradation may result in capacity loss as well as power loss. Blocking of active site due to formation of resistive surface layer or loss of electrical contact and particle cracking may result in the unavailability of active mass of anode (Birkl et al. 2017).

Loss of active material of cathode: Loss of electrical contact or particle cracking and structural disordering may lead to this mode of degradation resulting in capacity as well as power loss (Birkl et al. 2017).

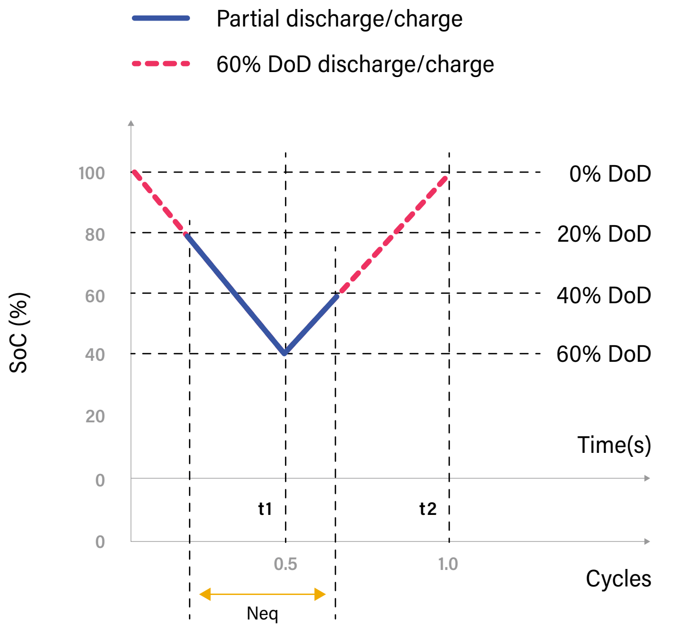
Counting battery cycle

Battery warranty is mentioned in terms of number of battery cycles (full equivalent cycles) or years. Here, the battery cycles are calculated when the battery is subjected to a repetitive discharge-and-charge cycle at a given DoD, C-rate, and temperature.

As we know, for realistic load profiles, a discharge/charge cycle may not always start/end with a battery SoC of 100 percent, so the concept of equivalent number of cycles is introduced. The equivalent number of cycles for a given DoD is defined as the number of cycles equivalent to the scenario where the SoC at the beginning and end of cycle is 100 percent (Motapon et al. 2020).

For example, if the battery is discharged from 80 percent SoC (20 percent DoD) to 40 percent SoC (60 percent DoD) and then recharged to 60 percent SoC (40 percent DoD), the cycle's DoD is 60 percent and the equivalent number of cycles can be calculated by the formula given below:

Figure A2 | **Calculating equivalent number of cycles**



$$Ne_q = 0.5\left(2 - \frac{DoD\ (n-2) + DoD\ (n)}{DoD\ (n-1)}\right)$$

$$Ne_q = 0.5\left(1 - \frac{20\%}{60\%}\right) + 0.5\left(1 - \frac{40\%}{60\%}\right) = \mathbf{0.5}$$

Source: Motapon et al. 2020.

Charge/discharge rate (C-rate)

The charge rate of batteries is calculated by taking into account the charger power and the battery capacity using the formula given below:

$$C - rate = \frac{\text{Charger power (kW)}}{\text{Battery capacity (kWh)}}$$

For example, consider a 15 kWh battery pack:

- 1C rate refers to pumping in 15 kW of charge resulting in a full charge in 1 hour. Here a charger power rating of 15 kW is required to charge at 1C.
- 2C rate refers to pumping in twice the charge—i.e., 30 kW. Therefore, the battery will be charged in 0.5 hours. Here, charger power rating of 30 kW is required to charge at 2C.

Charging at C-rate < 1C is termed slow charging, whereas charging at C-rate ≥ 1C is termed fast charging.

Similarly, the discharge rate of batteries is calculated taking into account the power drawn by the vehicle and the battery capacity.

$$C - rate = \frac{\text{Power required by vehicle (kW)}}{\text{Battery capacity (kWh)}}$$

For example, consider a 15 kWh battery pack:

- If the vehicle requires 15 kW of power, it means that the battery is being discharged at a 1C rate. The battery would be completely discharged in 1 hour.
- If the vehicle requires 60 kW of power, it means that the battery is being discharged at 4C. Therefore, the battery will be discharged in 0.25 hours.

ANNEX B. BATTERY LIFE ANALYSIS: DATA COLLECTION TEMPLATE

The performance and safety of electric vehicles (EVs) are greatly influenced by the state of their battery. Monitoring and understanding the battery performance under the influence of local driving, usage, and environmental conditions can help in developing a strategy to improve battery life and the economic viability of the vehicle. Following are templates to collect data for the battery life analysis. Note that the frequency of data collection can be decided based on the trade-off between the cost and benefit analysis of data collection and management.

Table B1 | **Technical details**

	TECHNICAL SPECIFICATION
Vehicle	Vehicle number/e-bus ID:
	Bus type & dimension:
	Assured range (km):
Battery	Capacity & chemistry:
	BMS & TMS details:
	Assured cycle life (n):
Charger	Charging standard:
	Number of chargers per bus (slow & fast):
	Slow charger (kW):
	Opportunity charger (kW):

Source: Authors' analysis.

Table B2 | **Vehicle operational details**

MONTHS	NO. OF DAYS	AVERAGE AMBIENT TEMPERATURE (°C)	DISTANCE COVERED (km)		DRIVE CYCLE		
			Average/day	Max/day	Average speed (km/h)	Max speed (km/h)	Stop time (en-route*)(hh:mm)
January							
February							
March							
April							
May							
June							
July							
August							

MONTHS	NO. OF DAYS	AVERAGE AMBIENT TEMPERATURE (°C)	DISTANCE COVERED (km)		DRIVE CYCLE		
			Average/day	Max/day	Average speed (km/h)	Max speed (km/h)	Stop time (en-route*)(hh:mm)
September							
October							
November							
December							

Note: *Stop time includes scheduled halts and the time for which vehicle attains ~0 km/hr speed due to braking when driving.

Source: Authors' analysis.

Table B3 | Battery energy details

MONTHS	ENERGY (kWh)		SOC (%)			BATTERY CAPACITY (kWh)	SOH (%)
	Consumption by battery	Generated from RB*	Average	Maximum	Minimum	@100% SoC	
January							
February							
March							
April							
May							
June							
July							
August							
September							
October							
November							
December							

Note: *Regenerative braking.

Source: Authors' analysis.

Table B4 | Battery operational details

MONTHS	BATTERY POWER (kW)		BATTERY TEMPERATURE (°C)			CHARGE RATE (C-RATE)	
	Average power	Max. power	Average	Maximum	Minimum	Slow charging	Opp. charging
January							
February							
March							
April							
May							

MONTHS	BATTERY POWER (kW)		BATTERY TEMPERATURE (°C)			CHARGE RATE (C-RATE)	
	Average power	Max. power	Average	Maximum	Minimum	Slow charging	Opp. charging
June							
July							
August							
September							
October							
November							
December							

Source: Authors' analysis.

Table B5 | **Charging details**

MONTHS	AVERAGE CHARGING SESSION PER DAY (HH:MM)		AVERAGE ELECTRICITY CONSUMPTION PER BUS (kWh)
	Slow charging	Opp. charging	
January			
February			
March			
April			
May			
June			
July			
August			
September			
October			
November			
December			

Source: Authors' analysis.

ABBREVIATIONS

BCN	Barcelona
BMS	Battery Management System
BTMS	Battery Thermal Management System
CAGR	Compound Annual Growth Rate
C-rate	Charge/Discharge Rate
CTP	Cell to Pack
DoD	Depth of Discharge
E-bus	Electric Bus
EV	electric vehicle
EDAS	Eco-Driving Assistance System
EoL	End of Life
EV	Electric Vehicle
FAME	Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles
GoI	Government of India
GOT	Gothenburg
IEMS	Intelligent Energy Management System
ITDP	Institute for Transport and Development Policy
KPI	Key Performance Indicator
LFP	Lithium Iron Phosphate
LIB	Lithium-ion Battery
LMO	Lithium Manganese Oxide
LTO	Lithium Titanium Oxide
NEBP	National Electric Bus Program
NMC	Lithium Nickel Manganese Cobalt
OEM	Original Equipment Manufacturer
OSN	Osnabrück
PIB	Press Information Bureau
RBS	Regenerative Braking System
SEI	Solid Electrolyte Interphase
SoC	State of Charge
SoH	State of Health
SRTUs	State Road Transport Undertakings
TCO	Total Cost of Ownership
TMS	Thermal Management System

ENDNOTES

1. Regenerative braking converts a substantial portion of the kinetic energy lost during deceleration into stored energy of EVs by using the motor of the vehicle as a generator. This energy can be used in the future, improving the efficiency of a vehicle.

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