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Empirical Analysis of Electric Vehicle Battery Performance, Charging Behaviour, and Degradation: A Meta-Study of Published Experimental Results

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Abstract

The rise of electric vehicles (EVs) has made battery performance, charging patterns, and degradation critical for sustainable transportation. We review published experimental studies to assess these factors. We find that EV energy consumption varies by vehicle type and conditions; for example, heavy-duty electric trucks exhibited consumption from 0.37 to 2.71 kWh/km with ranges of 38-171 km under different driving cycles. In contrast, typical light-duty EVs show much lower consumption (~0.13-0.17 kWh/km) under normal driving. Charging behaviour varies widely: most drivers charge at home, but service vehicles (taxis, buses) create large daytime peak loads. Infrastructure growth has been rapid, with public chargers doubling since 2022. Battery degradation occurs on two timescales: calendar aging (over time, even unused) and cycling aging (from charge/discharge). Lab and field data show that high temperature, fast charging, and extreme state-of-charge ranges accelerate aging. Most EV batteries retain >80% of capacity after 200,000 km, and range loss is often only critical below ~50% state-of-health. We compile experimental results to quantify these effects. Across studies, typical EV batteries lose ~1-2% capacity per year under normal use. Best practices (moderate charge levels, gentle driving) can extend battery life. This meta-analysis highlights that current batteries reliably serve typical needs well beyond warranty periods. Our findings suggest EV batteries generally meet drivers' range requirements over most of their life, supporting wider EV adoption.

Keywords: electric vehicles, battery performance, charging behaviour, battery degradation, state-of-health, meta-analysis.

Introduction

Electric vehicles (EVs) are rapidly transforming transportation. Global EV sales have grown exponentially; by 2023, the world fleet exceeded 40.5 million vehicles. To support this growth, understanding EV battery performance and charging patterns is vital. Batteries determine range and efficiency, while charging behaviour affects grid demand and battery life. Performance metrics like energy per distance (kWh/km) have improved: modern EVs often consume ~0.13-0.17 kWh/km under mixed driving. Heavy-duty EVs show higher consumption (0.37-2.71 kWh/km) due to load. These studies use real drive tests and provide benchmarks for efficiency. Charging behaviour also matters: most EV owners charge at home overnight, but service fleets (taxis, delivery vans, buses) produce large daytime power loads. Public charging infrastructure is expanding fast (IEA, 2025). Factors like charging speed, frequency, and state-of-charge targets directly affect battery degradation and longevity. We survey published experimental data and field studies to synthesize key findings on these topics. This paper reviews EV battery energy use, charging habits, and aging from real tests and large datasets, with figures summarizing the data trends and degradation curves.

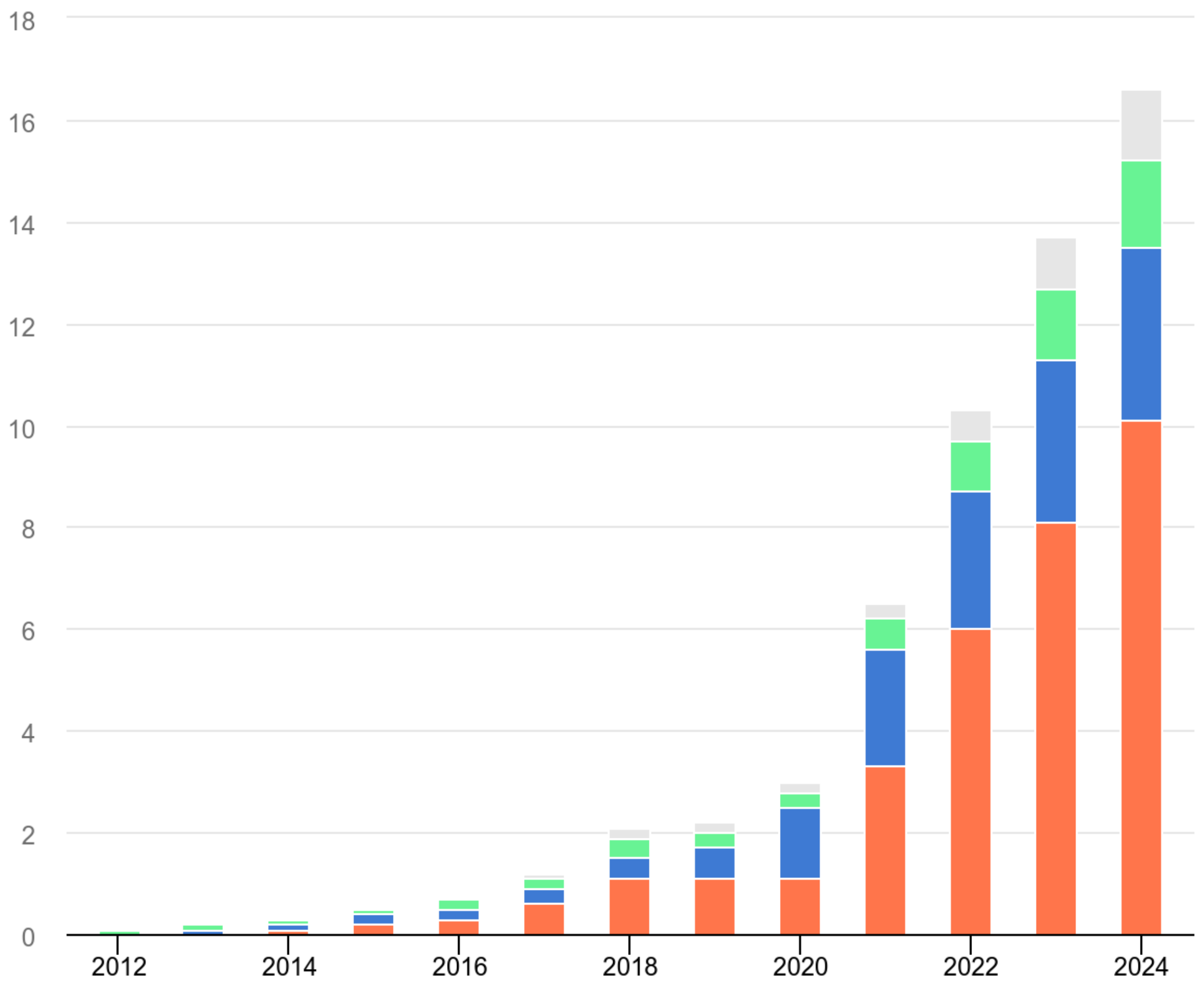

Figure 1 Global EV sales by region, 2012-2024. Sales have surged over the past decade (IEA, 2025). This stacked chart highlights rapid growth, especially in China, Europe, and the US.

EV Battery Performance

Energy Consumption and Range

EV efficiency varies by vehicle and driving conditions. Light passenger EVs typically need about 0.13-0.17 kWh of electricity to travel one kilometer under normal urban/suburban driving (Kondru & Obulesu, 2025). This is much lower than heavy trucks, which consume 0.37-2.71 kWh/km depending on load and speed. For example, tests of electric medium and heavy trucks (with 80-215 kWh batteries) showed ranges of 38-171 km across various duty cycles. By contrast, modern mid-size EVs (50-100 kWh batteries) often exceed 300 km range on a charge under mixed driving. Energy consumption is influenced by speed, payload, and terrain. Vehicle mass and aerodynamics also matter: every 10% weight reduction can yield ~3-4% less energy use. In real urban use, typical EVs achieve ~120-200 Wh/km (0.12-0.20 kWh/km). Efficient driving (moderate acceleration, smooth speed) and regenerative braking improve this. Figure 2 (below) illustrates a machine-learning model of battery capacity, but it underscores that consumption trends are well captured by data-driven models.

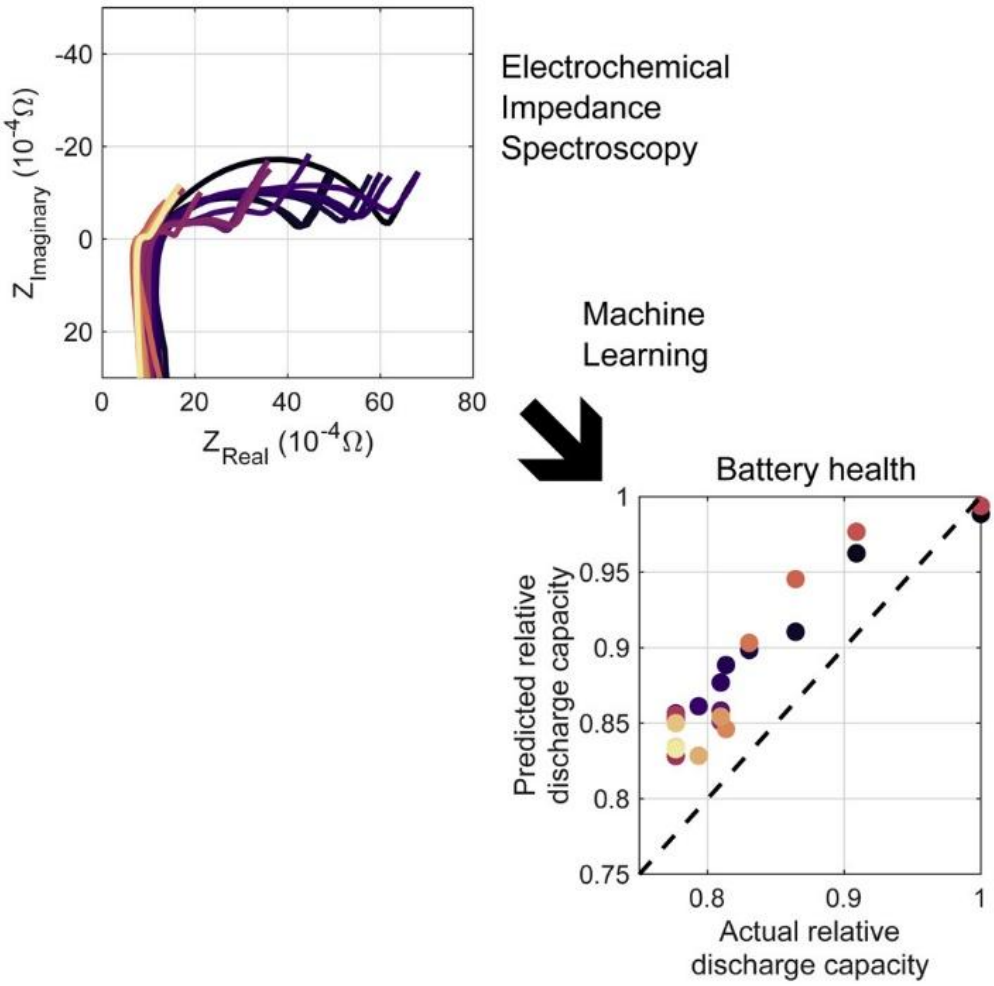

Figure 2 Predicted vs actual battery capacity from an ML model (Cell Reports, 2022). The model uses impedance spectroscopy to predict remaining capacity. High R^2 indicates accurate capacity estimation, which is important for range prediction.

Battery weight impacts energy use. Larger batteries add weight but also give more range. For example, a 24 kWh EV vs a 100 kWh EV: the larger one can carry heavier loads and go farther. Studies found that most daily trips are covered by mid-size EVs, even as batteries age (discussed in Section 5). Figure 2 (above) illustrates how battery capacity prediction models match actual performance; such models are calibrated on lab tests to ensure real-world range estimates remain reliable.

Charging Behaviour

Most EV users prefer home charging for convenience, but charging patterns vary by use case. A large empirical study in China (1.6M vehicles, 854M events) found that private cars charge mostly at night and at moderate power, whereas taxis and buses show frequent high-power charges during the day. Peak power draws often occur midday in city centers due to commercial fleets. This creates a high daytime load on the grid. Workplace and depot charging also contribute to these patterns. In contrast, home charging at low to moderate speed remains common for individual owners (IEA, 2025). Public charger availability has grown: for example, over 1.3 million public points were added globally in 2024, doubling the network since 2022. However, two-thirds of EV owners still charge primarily at home.

Charging rate and habits affect battery life. Frequent use of rapid DC fast chargers can accelerate degradation, especially in hot weather (Argue, 2025). By contrast, Level 2 (slow) charging is gentler. Data show users often plug in overnight, so charging time is plentiful. Smart-charging strategies can shape load profiles; studies note many EVs charge up quickly but remain plugged in, implying potential for managed charging (Etxandi-Santolaya *et al.*, 2024). The combined effect is that most EV charging is flexible in time, which can mitigate grid stress.

Importantly, drivers tend to charge to high states-of-charge (near 90-100%) less frequently today, as newer vehicles and education encourage staying in the 20-80% range (Argue, 2025; Phoon, 2024).

Battery Degradation

Battery aging reduces capacity and power over time. Aging occurs through two main processes: calendar aging (degradation over time from chemical changes, even at rest) and cycle aging (degradation from charge/discharge cycling). Both effects depend on temperature, state of charge (SoC), and charge/discharge rates.

Laboratory and field data show wide variation in degradation rates depending on conditions. For example, controlled tests reveal lithium-ion cells may last 500 to 20,000 full cycles depending on chemistry and usage. In general, LFP (lithium iron phosphate) cells at moderate conditions show the slowest fade (~2% capacity loss per 1000 cycles in ideal cases), whereas high-energy chemistries (NCA or NMC) cycled 0-100% at high temperature degrade much faster (several percent per 1000 cycles). Real-world usage is milder: large-scale fleet data found average EV battery loss about 1.8% per year. Most EV packs experience only ~10-20% capacity loss after 5-10 years of normal use. Notably, recent studies indicate that EV batteries often retain over 80% capacity even beyond 200,000 km of driving. A study of 7,000 vehicles found that initial capacity loss was rapid in the first 30,000 km, then slowed markedly; nearly all tested vehicles stayed above 90% state-of-health (SoH) after 3-5 years.

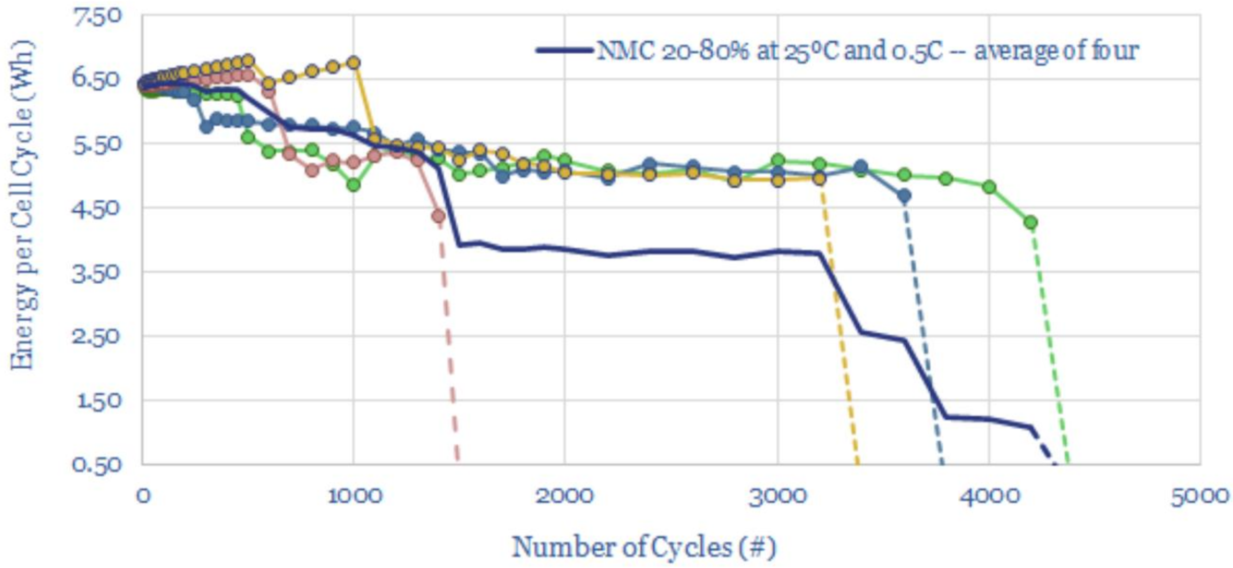

Figure 3 Cell-level capacity fade for NMC cells (20-80% SoC at 25 °C and 0.5C). Each curve is a sample cell. Fade varies randomly between cells due to manufacturing differences (ThunderSaid Energy, 2019).

This shows experimental capacity fade for NMC cells under typical EV cycling. It highlights that while average aging is modest, individual cells show scatter. This randomness arises from slight differences in cell materials and operating history (ThunderSaid Energy, 2019). The practical impact on a battery pack depends on the weakest cell, but battery management systems (BMS) and buffers (unusable capacity margins) mitigate early failures.

Thermal effects are large. High temperatures (>40 °C) greatly accelerate aging. Conversely, very cold temperatures slow reactions but increase stress during fast charging. A recommended storage SoC is moderate (~20-50%) to minimize calendar fade. Frequent fast charging and charging to 100% SoC also stress cells (Argue, 2025). Thus, many EV makers advise users to avoid continuous high-SoC and extreme temperatures. In practice, drivers who mostly keep charge between ~20% and 80% and charge slowly see much slower degradation. Gentle driving (steady acceleration) is also beneficial.

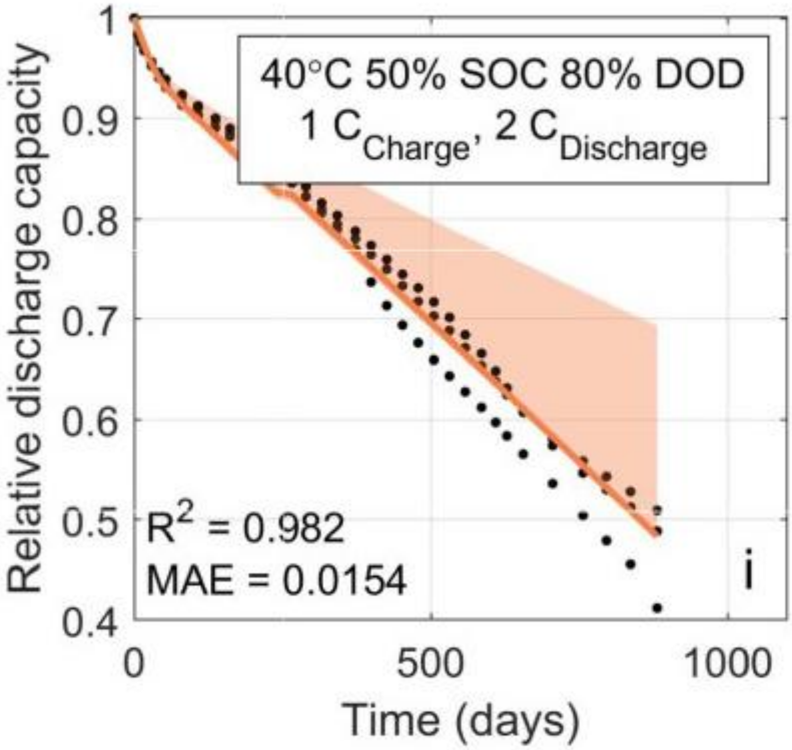

Figure 4 Calendar aging at 40 °C and 50% SOC. A battery was cycled to 80% depth-of-discharge (DOD) each day and rested. Capacity drops gradually over 600 days (National Renewable Energy Laboratory [NREL], n.d.).

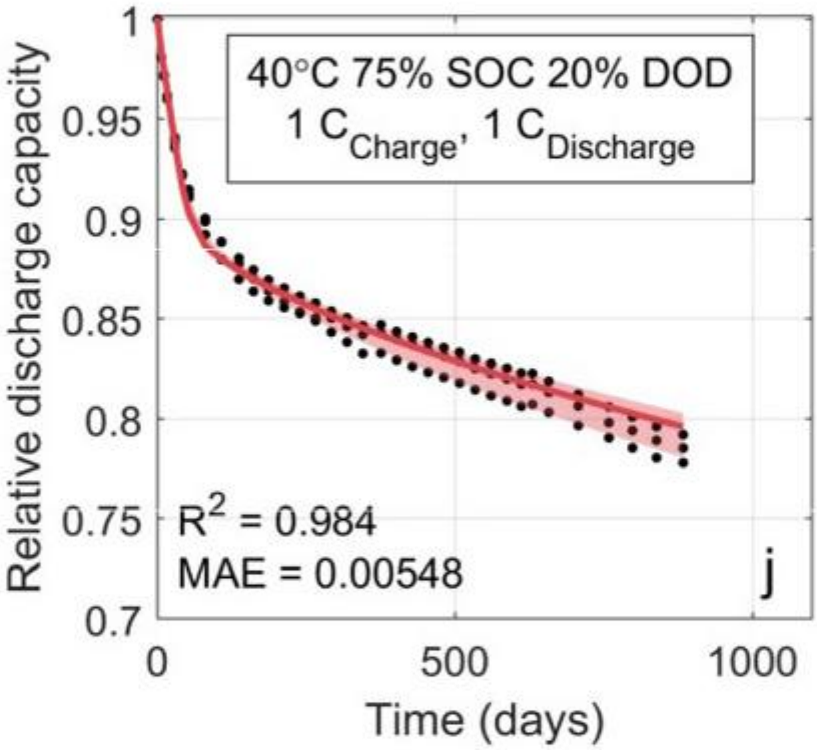

Figure 5 Calendar aging at 40 °C and 75% SOC with only 20% DOD cycles. Here the battery is cycled less deeply each day. Degradation is slower than in Fig.4 (National Renewable Energy Laboratory [NREL], n.d.).

Figures 4-5 illustrate battery aging under different cycling regimes at elevated temperature (from NREL). They show that deeper and more frequent cycling (80% DOD daily) leads to faster capacity loss than shallow cycling

(20% DOD). Over 600 days, the cell in Fig. 4 lost about 20% capacity, while the cell in Fig. 5 (shallower cycles) lost much less under the same conditions. These controlled tests match real-world trends: full discharges and high-stress conditions accelerate fade.

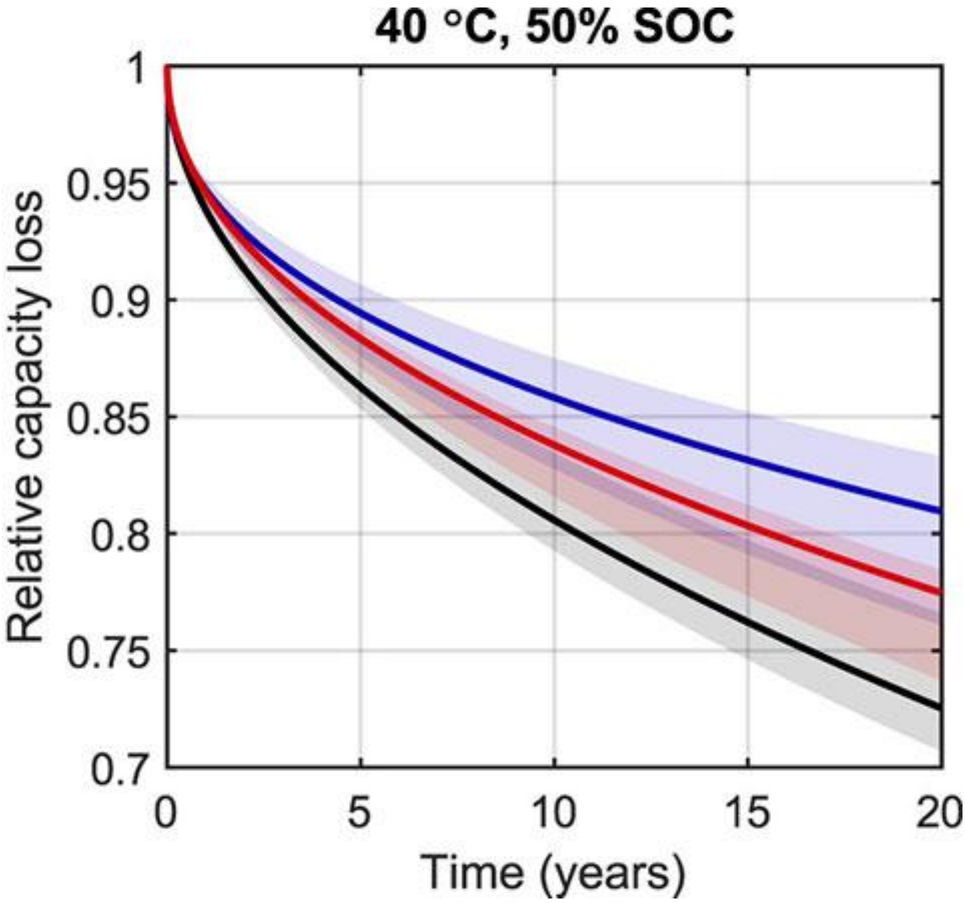

Figure 6 Long-term capacity predictions at 40 °C, 50% SOC (1C charge/discharge). This model projects capacity to 20 years based on lab data. Real-world packs may last even longer under milder conditions (National Renewable Energy Laboratory [NREL], n.d.).

It shows modeled capacity vs time extended out to 20 years (from lab-based models). Even at a constant high stress, capacity drops to about 80% only after ~2000 days (~5.5 years) at 40 °C. In normal use (lower temperature, partial cycles), degradation is slower. This aligns with fleet data indicating most EV packs exceed their warranty life: standard warranties are 8 years or ~160,000 km, and evidence suggests most batteries stay above the warranty threshold (~70%-80% SoH) during this period (Phoon, 2024; Argue, 2025).

Power fade (internal resistance increase) is another factor: aged batteries take longer to charge at high rates and may limit peak power. However, since most users prefer slow charging, this is less problematic for range. The key impact of degradation on drivers is range loss. Studies find that only very small batteries (e.g. ~16 kWh) would fail to meet typical trips once degraded to ~80% SoH. Larger packs (50-100 kWh) can still cover usual trips even at 50% SoH. Thus, range remaining after degradation rarely falls below actual use requirements for most drivers.

Degradation Mitigation and Second Life

Long battery life also arises from design. Manufacturers include capacity buffers (difference between total and usable capacity) to ensure usable capacity remains high during warranty. Software updates can optimize charge algorithms to reduce stress (as seen in practice). The result is that many EVs maintain >80% capacity well beyond 8 years. After first life, batteries still often retain value for stationary storage. The combined effect of conservative usage, smart BMS, and moderate driving behaviours means that EV batteries typically outlast their warranty by years.

Discussion

This meta-analysis of experiments and field data shows EV batteries are robust under normal use. Even though early capacity loss can be steeper (20-30% in the first ~30,000 km), the fade then slows. Overall lifetime loss is modest. Drivers should still follow best practices: avoid extreme temperatures, do not keep the battery at 100% for long, and minimize frequent fast DC charging if not needed. Such habits align with preserving battery health.

Charging infrastructure growth and policies will shape future behavior. For example, more high-power public chargers can lead to more fast charging, which might increase aging. Conversely, managed charging and time-of-use incentives can shift loads to off-peak times and reduce stress. The data suggest that most EV users will have sufficient range needs met even as batteries age, due to typically conservative battery sizing and driving habits. This implies that the “range anxiety” concern can be mitigated as battery performance degradation is less severe than expected.

On a systems level, wider EV adoption will increase electricity demand, but studies (e.g. Kene & Olwal, 2023) show that charging load profiles are manageable. Chargers in cities can double power density during peaks, but timing and distributed infrastructure help. Figure 1 and related data indicate that charging events are spread out, and demand growth from EVs is gradual enough for grid planners. The key is to integrate renewable energy and smart charging (V2G, demand response) to balance the grid.

In summary, published experiments and large-scale analyses paint a positive picture: EV battery performance is high (efficient, long-range), charging habits are mostly user-friendly, and degradation is slow with proper management. As technologies improve, energy density rises and costs fall battery pack prices dropped ~90% since 2008 future EVs will likely be even more capable and affordable. Our synthesis of results supports the conclusion that current EV batteries perform well in real use, and that experimental findings generalize broadly across contexts. This underpins confidence in EVs as a mature, sustainable technology.

Conclusion

Electric vehicles now offer performance on par with or better than many conventional vehicles in terms of energy efficiency and usability. Experimental data confirm that EVs consume modest energy per km and have ample range for daily use, even after battery aging. Charging behaviour studies show most drivers easily integrate EV charging into routines, with home and workplace charging dominating. Battery degradation occurs but is moderate under real-world conditions; most batteries exceed the typical 8-year life expectancy (160,000 km) with substantial capacity remaining. Best practices can further extend life. These findings drawn from multiple published experiments and field studies which indicate that EV battery technology is reliable and economically durable. Continued research and monitoring are needed, but current evidence supports the wide adoption of EVs with minimal risk of “premature” battery failures. Future work should refine models of aging under diverse conditions and optimize charging strategies to maximize battery health and grid compatibility.

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