

Unlocking fast-charge performance in high-energy EV batteries.

Managing electrochemical margins to enable fast charging in long-range EV batteries



Executive summary

EV customers now expect approximately 500 km of real-world range and charging experiences under 20 minutes. According to [McKinsey's 2025 Mobility Consumer Pulse](#)¹ survey, longer driving range is the single most important factor that would convince non-EV owners to switch, cited by 43% of respondents across Europe, the United States, and China. At the same time, willingness to pay a premium is falling: the majority of buyers in Europe and the United States now expect price parity with combustion vehicles.

Higher energy density is essential to meeting range targets, but it also narrows the safe operating window for fast charging. Thicker electrodes, denser materials, and larger cell formats slow lithium transport and concentrate heat generation. Conventional battery management systems base their charging strategies on surface-level measurements, using lookup tables indexed by state of charge and temperature, without estimating the internal electrochemical states that actually govern plating risk. The result is wide safety margins that restrict usable performance.

> THE CORE INSIGHT:

**MANY HIGH-ENERGY CELL DESIGNS COULD
SAFELY CHARGE FASTER THAN THEY DO TODAY.**

Hardware sets the physical limits of what a battery can deliver. Software determines how much of that capability can be safely accessed. Breathe Charge uses a proprietary physics-based model to estimate internal cell states in real time, then regulates charging current to maintain precise safety margins throughout life. This unlocks performance that static lookup tables force OEMs to leave unused.

> KEY FINDING:

Closed-loop margin control delivered a **38% improvement in ten-minute range** added and a **30% improvement in the 10-80% fast charging time** compared to lookup-table strategies, while maintaining the same level of durability throughout the battery's life.

Breathe Charge is in mass production on the Volvo ES90

¹New twists in the electric-vehicle transition: [A consumer perspective, McKinsey, 2025](#).

The market reality: Rising expectations, narrowing margins

What customers expect today

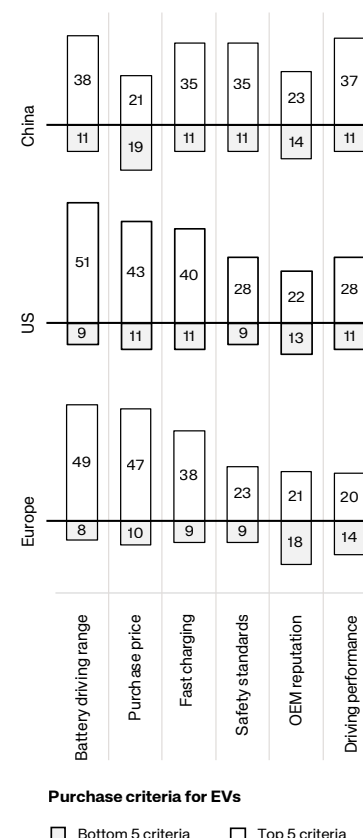
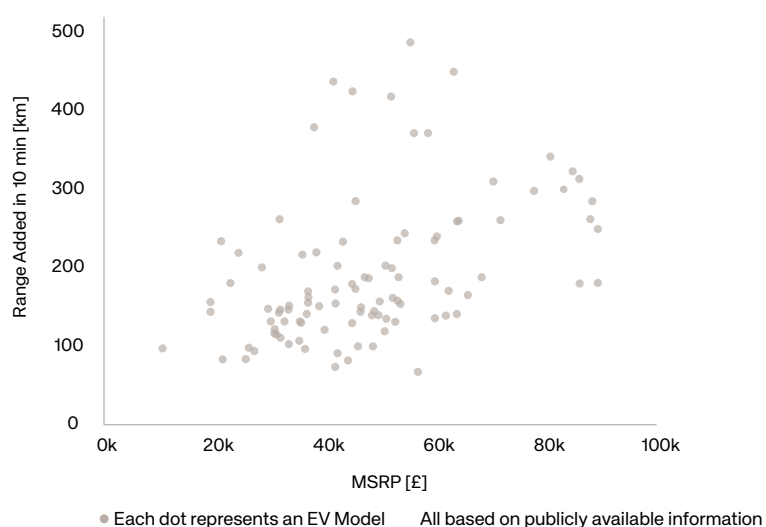
McKinsey's 2025 Mobility Consumer Pulse survey, covering 19,491 respondents across China, Europe, and the United States, reveals clear and rising expectations for EV performance:

- **Range:** 43% of non-EV owners say longer driving range would tip the balance toward an EV purchase, the highest-ranked factor. The average minimum acceptable range has risen to approximately 500 km, up from 425 km in 2022.
- **Charging speed:** A third of prospective EV buyers expect charging times of 20 minutes or less. Most consider 30 minutes sufficient for an 80% charge on a highway charger, but expectations are rising as new 800V models demonstrate faster charging is possible.
- **Price:** Only about a third of European and American respondents are willing to pay any premium for an EV over a comparable ICE vehicle. The majority expect price parity or lower prices.

These three expectations (range, charging speed, and price) must now be delivered together. Range and fast charging are no longer independent attributes; they must improve simultaneously within constrained cost, mass, and packaging envelopes.

The competitive gap

Analysis of publicly available data across approximately 146 production EVs reveals a striking pattern: for vehicles with similar range, fast-charging performance varies widely.



> KEY FINDING:

Range added in 10 minutes is a comparable fast charging metric that puts the driver's experience first.

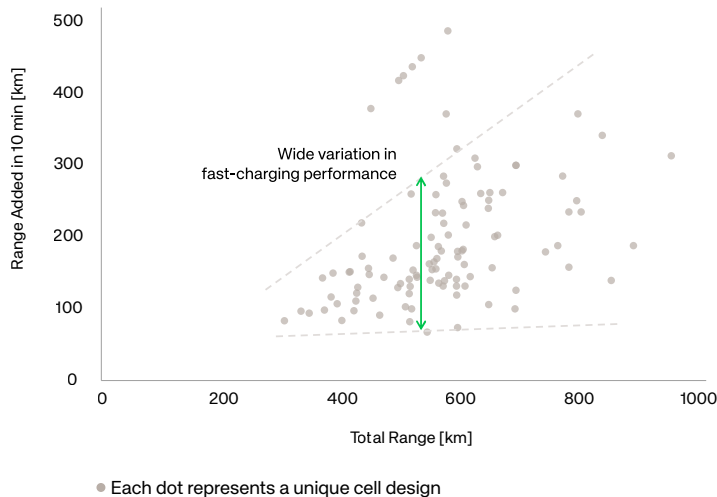
The price to performance ratio of range added in 10 minutes is broken by several OEMs, most notably XPENG (G6 and G9) and BMW Neue-Klasse platform (iX3)).

Range refers to WLTP combined range.

All data comes from publicly available information.

At the 500 km range point, now the baseline customer expectation, ten-minute range added varies from approximately 100 km to over 250 km.

Some of this variation reflects hardware differences. The fastest-charging vehicles typically combine advanced cell materials (such as high-rate graphite), optimised electrolytes, and superior thermal systems. Chemistry and hardware advances will continue to push the upper envelope of what is possible.



> KEY FINDING:

For vehicles with similar energy density and range, fast charging performance varies widely across OEMs, brands and platforms.

This spread reflects how varied each OEM's appetite for risk is, and how uneven their ability is to meet charging performance expectations while protecting battery health, reliability and quality.

Range refers to WLTP combined range.

All data comes from publicly available information.

But hardware alone does not explain the spread. Vehicles with comparable chemistries, cell formats, and pack capacities deliver very different charging performance. The vertical spread at any given range point reflects differences in control precision: each OEM's ability to access their hardware's capability while protecting battery health and reliability.

This suggests that control strategy, not just hardware, plays a decisive role in fast-charging performance. The following sections examine why.

Why this matters for western OEMs

This performance gap has commercial consequences. McKinsey's data shows that EV buyers are significantly more likely to switch brands than ICE buyers. In China, almost two-thirds of car buyers switch brands regardless of segment. In Europe and the United States, switching rates are higher for premium vehicles, the segment where fast-charging performance matters most.

A growing fraction of consumers search first for vehicles that meet their desired specifications (range, charging speed, price), then look for a brand that satisfies them. Fast-charging performance directly affects customer-facing metrics that influence purchase decisions and residual values. OEMs that can safely extract more performance from the same hardware gain competitive advantage without additional cell and pack cost.

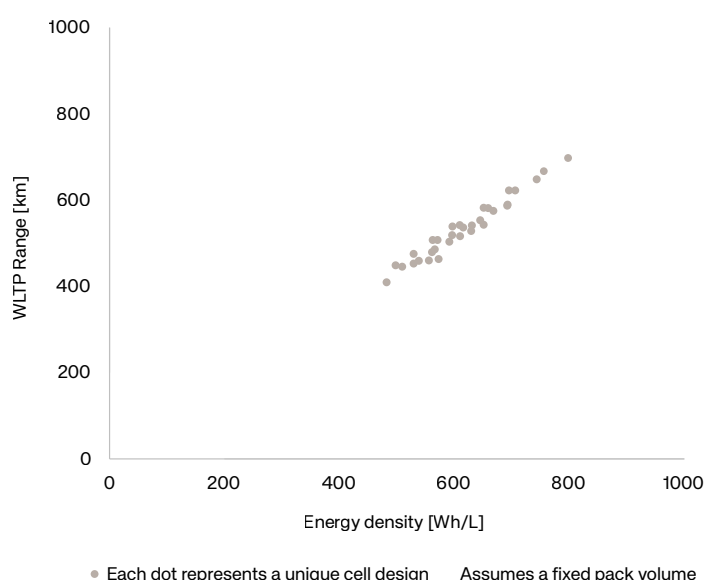
> WHY?

TO UNDERSTAND WHY THIS PERFORMANCE GAP EXISTS, AND HOW TO CLOSE IT, WE NEED TO EXAMINE HOW HARDWARE AND SOFTWARE INTERACT IN FAST CHARGING.

Hardware and software: Where performance is won and lost

Hardware sets the limits

The physical limitations of what a battery can deliver are dictated by the design of its hardware. Cell chemistry, electrode loading, porosity, format, and thermal architecture together define the outer boundary of what is possible.



> KEY FINDING:

Routes to increased energy density also increase the electrochemical sensitivity of the cell during fast charging:

- **Thicker electrodes** extend lithium diffusion paths, slowing transport into the anode bulk
- **Higher calendaring and electrode density** reduce pore volume, increasing ionic resistance
- **Silicon-containing anodes** undergo volume changes that alter pore structure over time
- **Larger cell formats** require heat to travel farther to reach cooling surfaces
- **Reduced inactive volume** concentrates heat generation into smaller physical domains.

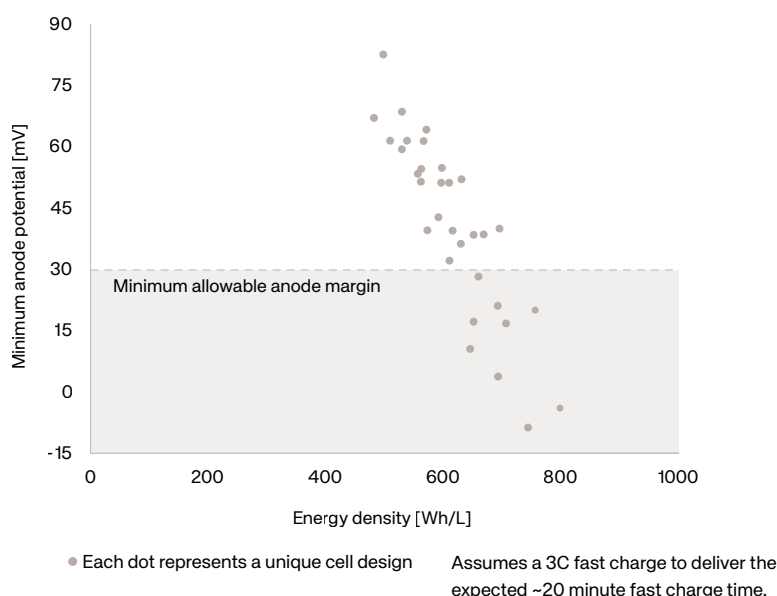
Higher energy density is the primary path to delivering the range customers expect within the constraints of vehicle packaging and a specified cell format. Several design levers contribute: higher electrode loading, increased active material density, reduced inactive volume, and larger cell formats. Each pathway delivers more stored energy per unit volume.

During high-rate charging, lithium arrives at the anode surface faster than it can diffuse through these constrained pathways. This creates steep concentration gradients that drive local anode potential toward the plating threshold. Once metallic lithium begins to deposit, capacity fades, internal resistance rises, and safety margins erode.

The hardware is capable of high performance, but the **safe operating window narrows** as energy density rises.

Software determines how much capability is accessible

The physics explains why control precision matters more as energy density rises. Simulation across a range of cell designs shows that as volumetric energy density increases, the minimum anode potential during fast charging drops, pushing cells closer to the plating threshold.

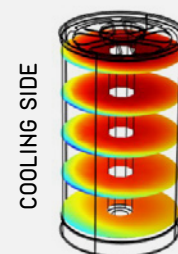


> KEY FINDING:

Determining the anode potential margin required during fast charging is critical.

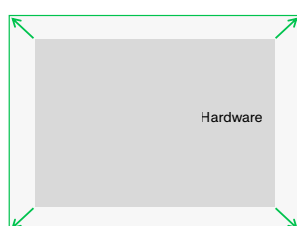
3D thermally-coupled simulation contribute to developing the required anode potential margin.

The heterogeneity is used to define the margin needed in the bulk anode potential.



At lower energy densities (~500 Wh/L), most cell designs operate with comfortable margin above the plating threshold, while delivering on the ~20 minute fast charge performance of the modern EV buyer. At higher energy densities (~700+ Wh/L), many designs sit within or near the risk zone. For these cells, small errors in control, or inability to adapt to aging, can push the anode potential into damaging territory.

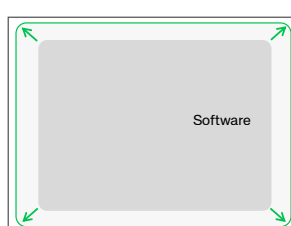
HARDWARE SETS THE LIMITS



Limits

The physical limitations of what performance a battery can deliver is dictated by the design of its hardware.

SOFTWARE NAVIGATES MARGINS



Margins

The ability to safely make use of the performance a battery is capable of is determined by the fidelity of the estimation and control software employed.

Software determines:

- **What margins are managed:** which internal states the system tracks and regulates
- **The precision of those margins:** how tightly safety buffers can be maintained
- **How margins evolve over life:** whether the system adapts to aging, temperature variation, and cell-to-cell divergence

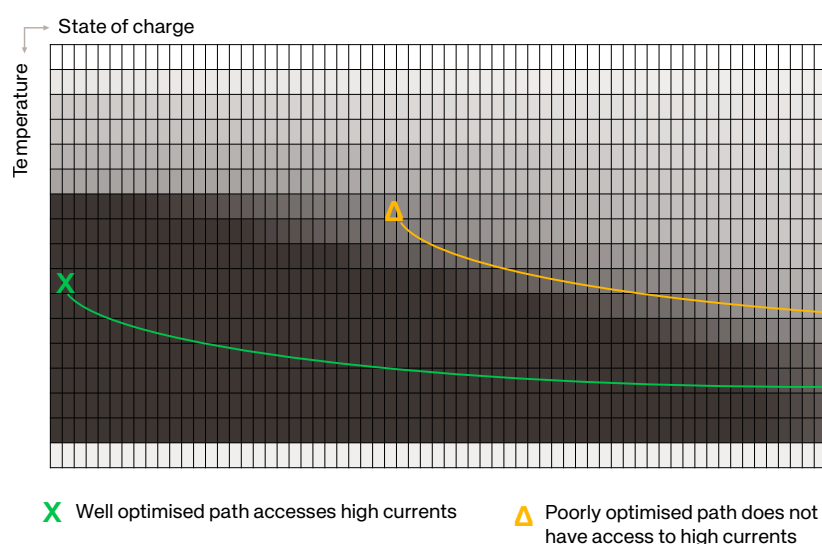
The same cell hardware can deliver very different fast-charging performance depending on how it is controlled. This is why the fastest-charging vehicles need both cutting-edge hardware and precise control. Hardware advances push the upper envelope; control precision determines whether that envelope can be safely accessed.

How conventional control works today

To understand why control precision varies so widely, it helps to understand how conventional battery management systems approach fast charging.

The quantity that governs plating risk is the anode potential, specifically how close it gets to the threshold where metallic lithium begins to deposit. This potential is shaped by lithium transport, local temperature, reaction kinetics, and the cell's aging state. It exists inside the electrode structure and cannot be measured directly by sensors on the cell terminals.

In principle, anode potential can be estimated from surface measurements (voltage, current, temperature) using physics-based models. In practice, most production BMS systems do not perform this estimation. Instead, they use lookup tables that map state of charge and temperature directly to allowable charging current.



> KEY FINDING:

Lookup tables must define the optimal path of fast charging in advance.

This is a fundamental limitation of the look-up-table approach that punishes the driver for charging their vehicle outside of the prescribed optimal zone.

Path dependency is a complex (highly coupled) component of fast charging that is frequently overlooked in fast charge development.

These tables are calibrated with both simulation and in the lab under controlled conditions and encode pre-determined current limits that must be safe across:

- Cell and pack manufacturing variations
- Thermal heterogeneity across the pack
- The full range of expected aging pathways
- Variation in user behaviour and environmental conditions

At beginning of life, a well-designed lookup table can approximate optimal charging behaviour.

The question is: **what happens as the cell ages?**

This is where the limitations of static control become apparent.

Closed-loop control: Regulating to the margin

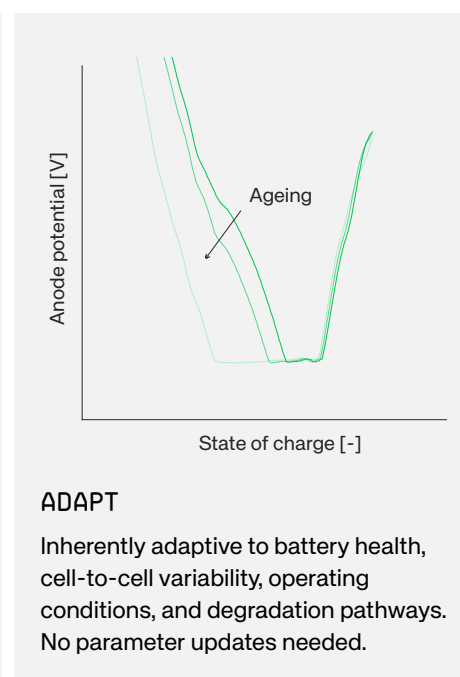
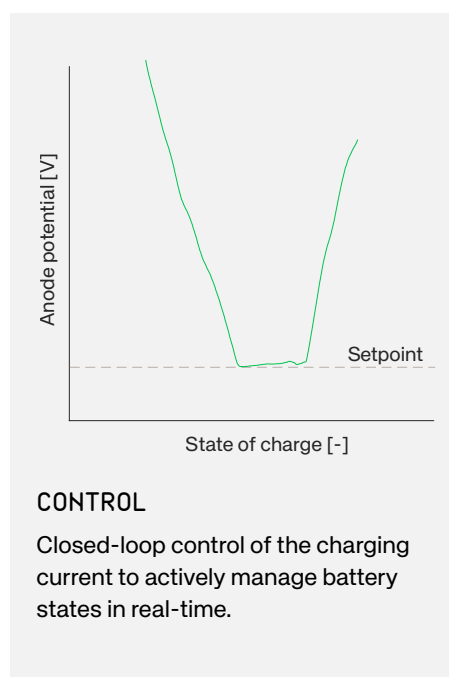
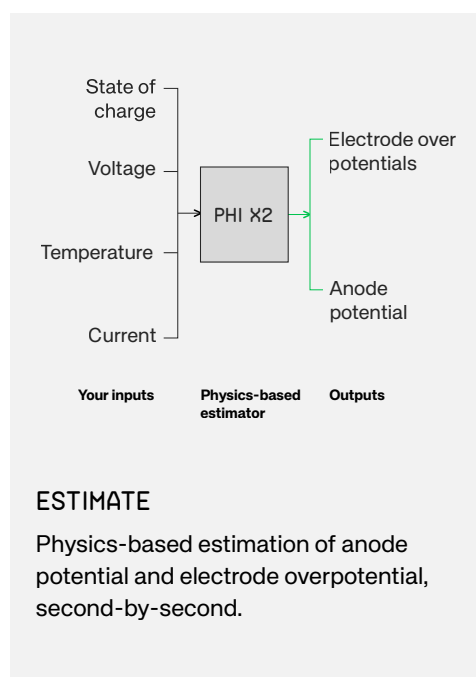
The principle

The lookup table dilemma can be resolved by controlling directly to the quantity that matters: the anode potential margin. This requires three capabilities:

1. **Real-time estimation** of internal electrochemical states using a physics-based model
2. **Closed-loop current regulation** to maintain a specified margin setpoint
3. **Inherent adaptation** to the cell's actual condition, including temperature, SOC, and aging state

The current profile is not predetermined. The margin is set, and the controller ensures conformity.

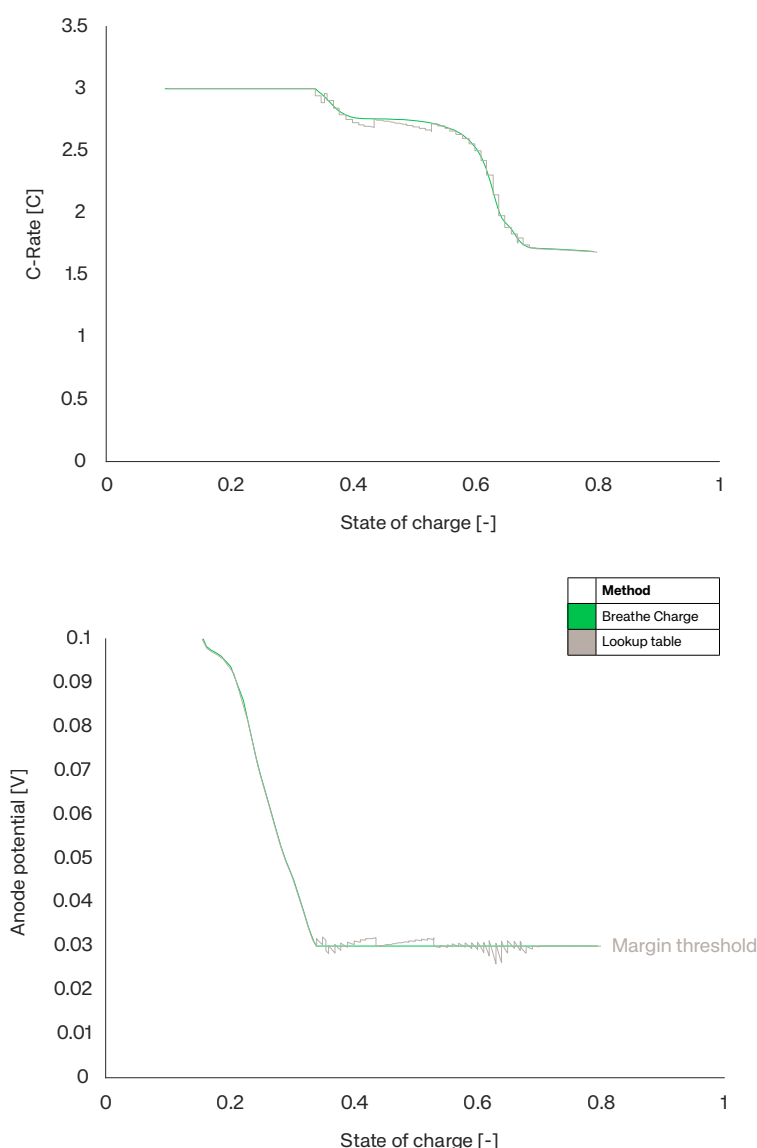
Breathe Charge implements this approach using a proprietary physics-based model that estimates internal states from a system's existing estimation (SoC) and measurements (temperature, voltage, and current).



The lookup table dilemma

Lookup tables work at beginning of life

A well-calibrated lookup table can approximate optimal charging behaviour when the cell is new. Simulation studies confirm that at beginning of life, a lookup table with typical automotive fidelity (5°C temperature breakpoints, 0.01 SoC breakpoints) tracks closed-loop control with reasonable accuracy, both in charging current and in maintaining the required anode potential margin.



> KEY FINDING:

At beginning of life, the current of the lookup table tracks that of Breathe Charge with reasonable accuracy.

A look up table was generated with 5°C breakpoints and 0.01 SoC breakpoints.

- 0.10 to 0.80 SoC under isothermal conditions.
- Stitched together the isothermal current traces.
- Representative of a modern automotive fast charge look up table in fidelity and structure.

> KEY FINDING:

The lookup table approach tracks the anode potential margin required with reasonable precision.

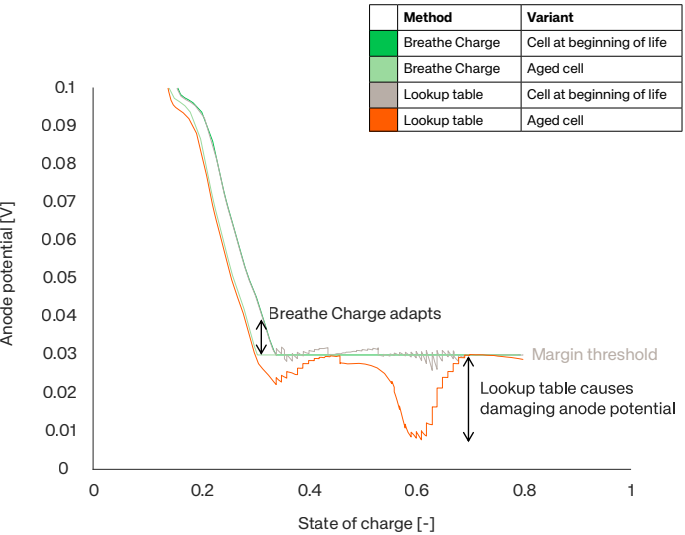
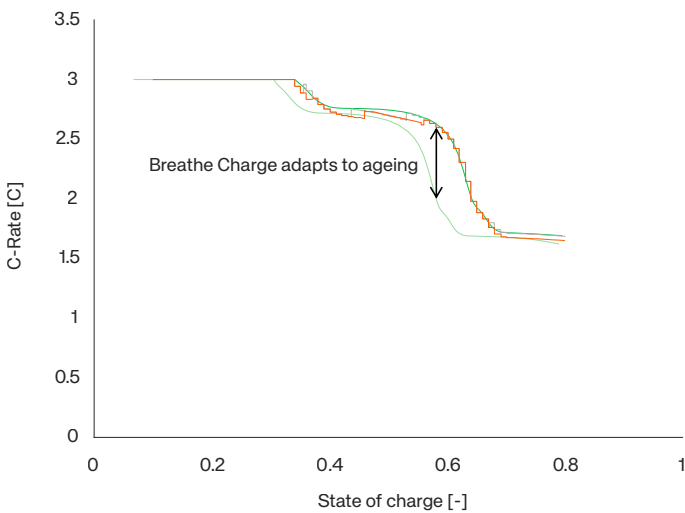
- The cell is at its beginning of life.

The problem is not that lookup tables are poorly designed. The problem is that they are **fragile** to aging.

The aging problem: A no-win scenario

Aging changes the internal behaviour of the cell, increasing resistance, reducing porosity, slowing lithium transport. A lookup table calibrated for beginning of life does not adapt to these changes. It continues to deliver the same current profile even as the cell’s safe operating window narrows.

The result: as the cell ages, the lookup table pushes the anode potential below the safety margin, into a regime where lithium plating becomes likely. This introduces cycle life, safety, and reliability concerns.



> KEY FINDING:

The cell was subjected to fast charging in an aged state with both Breathe Charge and the lookup table.

Breathe Charge adapts to the response of voltage, state of charge, and temperature in real-time to recommend the ideal charging current on a second-by-second basis.

The lookup table is insensitive to the ageing of the cell and delivers similar charging current as it did at the beginning of life.

- Lookup table is a function of cell temperature and state of charge.

> KEY FINDING:

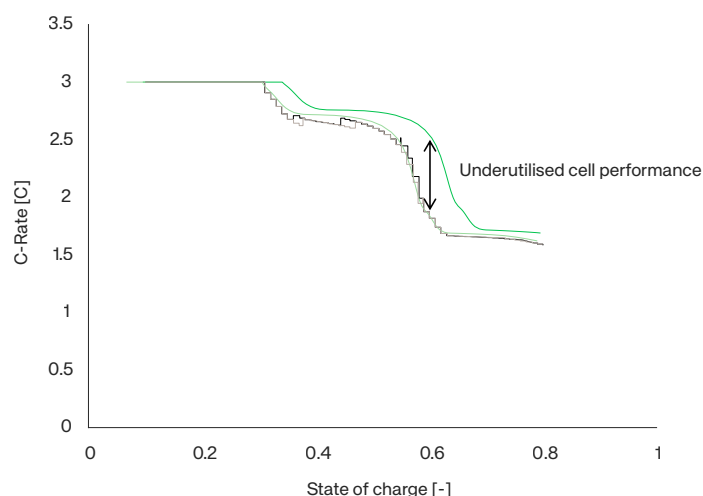
Breathe Charge never exceeds the set margin.

Breathe Charge inherently adapts to cell ageing conditions as estimation is performed in real time.

The lookup table exceeds the set margin as it was created based on the beginning of life characteristics of the cell.

- This introduces cycle life, safety, and reliability concerns.

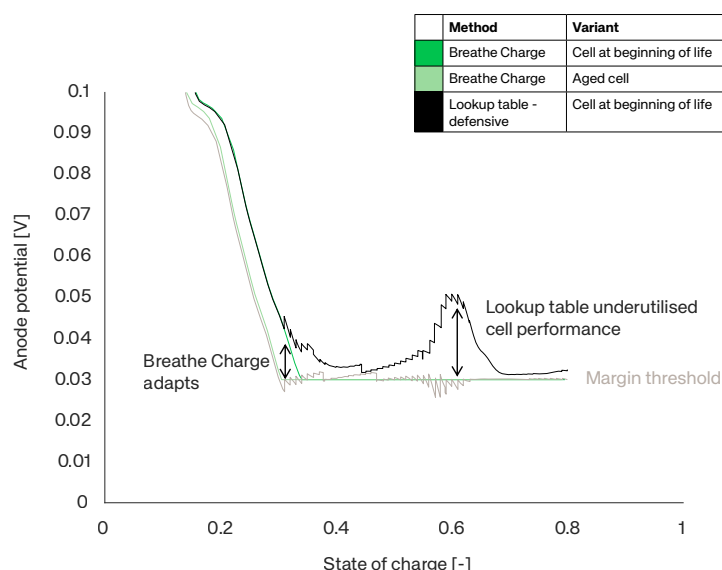
The obvious response is to calibrate the lookup table defensively, based on end-of-life behaviour rather than beginning of life. This protects the aged cell, but it creates a different problem: at beginning of life, current is reduced well below what the cell can safely accept. Performance is left on the table.



> KEY FINDING:

At the beginning of life, the lookup table delivers reduced current compared to Breathe Charge.

This means performance is being left on the table.



> KEY FINDING:

Defensive lookup tables do not make full use of the safe margins within the cell, the most expensive component of the vehicle.

- We are therefore carrying cost and performance that is dormant to the driver.

With Breathe Charge, the margin is always maintained by inherently adapting to the cells' condition:

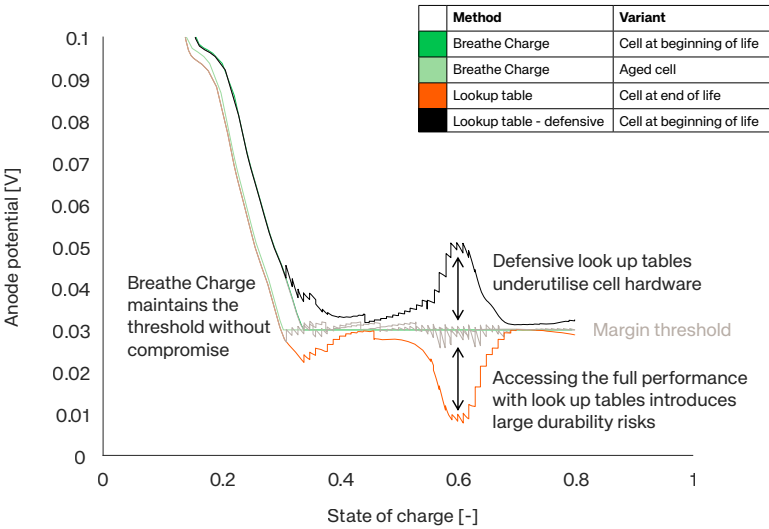
- Initial state of charge
- Temperature
- Aging state

This is the fundamental dilemma:

- **Calibrate for Beginning of Life (BOL):** Risk safety margin violations as the cell ages
- **Calibrate for End of Life (EOL):** Sacrifice performance throughout early and mid-life

No single lookup table calibration resolves this conflict. And this is just one aging pathway.

There are countless ways a battery can age in real-world use, depending on temperature history, charge patterns, depth of discharge, and cell-to-cell variation.



> **KEY FINDING:**

This single ageing state introduces a trade off to be made for a lookup table approach: defensive or risky.

- This is just a single ageing condition; there are an intractable number of ways a battery can age in an EV on the road

Breathe Charge has a margin specified and adapts to the battery in real time, no matter how it is being used or how it has aged, to maintain that margin.

Approach	BOL Performance	Aged Safety	Outcome
Lookup table (BOL calibration)	Full	Margin violated	Durability risk
Lookup table (EOL calibration)	Reduced	Protected	Unused capacity
Closed-loop margin control (Breathe Charge)	Full	Protected	Always optimal performance

The cost of conservatism

Most OEMs choose the defensive path. They calibrate for worst-case conditions to protect durability and warranty exposure. The result is that the battery, the most expensive component in an EV, carries cost and performance that is dormant to the driver.

The cell hardware is capable of more. The control strategy prevents access to it.

> HOW?
RESOLVING THIS DILEMMA REQUIRES A FUNDAMENTALLY DIFFERENT APPROACH TO CHARGING CONTROL.

Margin setpoints, not current tables

Because the physics-based estimator uses real-time measurements, it inherently adapts to how the cell has aged. There is no need for multiple calibration tables or aging models. The estimator sees the cell as it is now, not as it was when a lookup table was created.

The results demonstrate this directly:

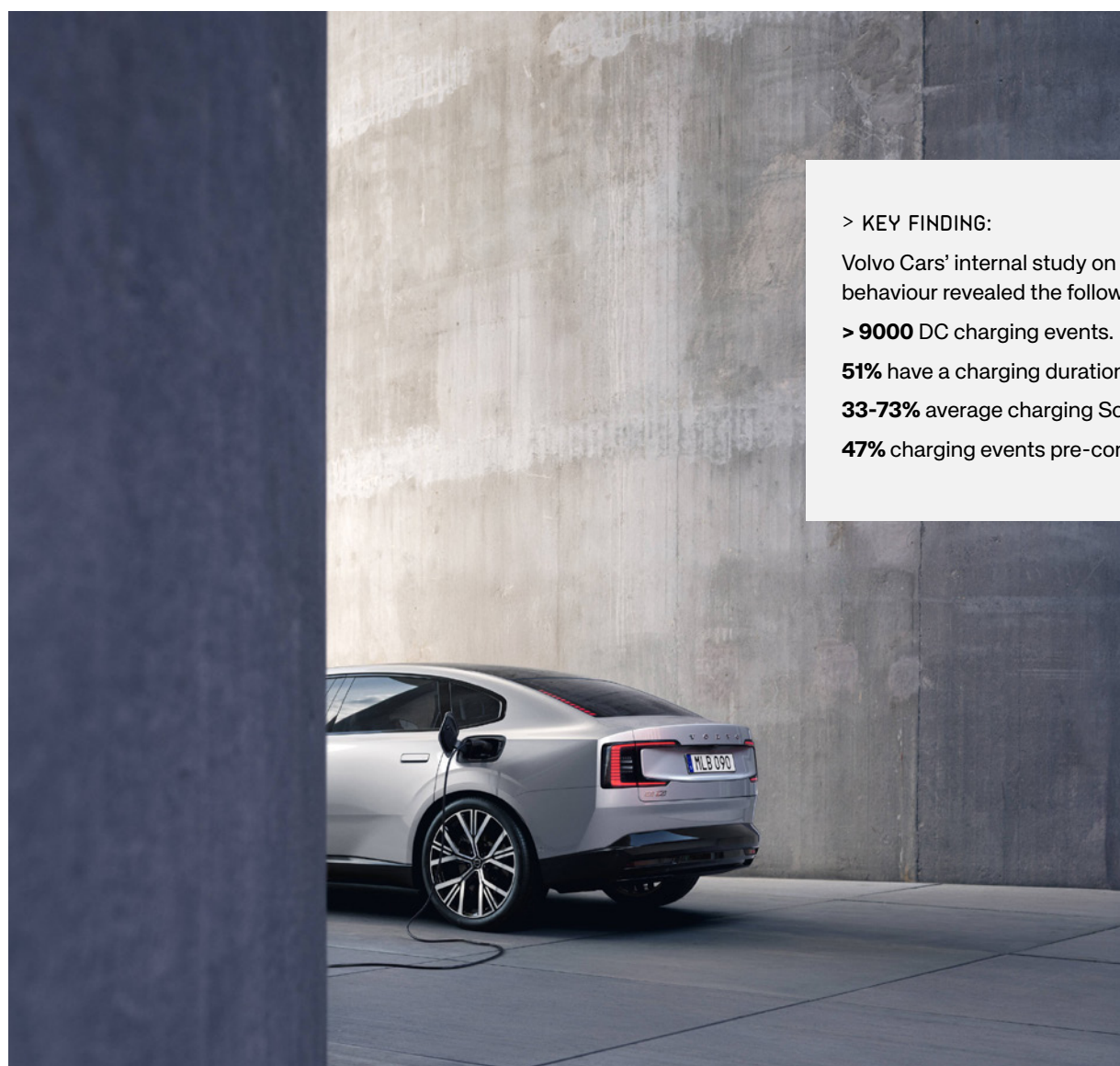
- At **beginning of life**, closed-loop control uses the full safe capability of the cell
- At **aged state**, the controller reduces current appropriately to maintain a healthy margin
- The **margin is never violated**, regardless of aging pathway

Validation: Real-world performance

Production deployment

Breathe Charge is deployed on the Volvo ES90, a high-energy platform targeting the European premium segment. A joint study published by both Breathe and Volvo demonstrates the performance benefits of closed-loop margin control compared to defensive lookup tables. The result is improved “headline” values, such as a 30% reduction in 10-80% charging time and a 38% improvement in range added in 10 minutes of charging. Not only this, but Breathe Charge also improves the real world vehicle charging experience by delivering high performance charging across a wide range of initial states of charge and ambient temperatures.

Source: Model-based and Health-adaptive Charging of Electric Vehicles, Volvo Cars, EVS38.



> KEY FINDING:

Volvo Cars' internal study on charging behaviour revealed the following trends:

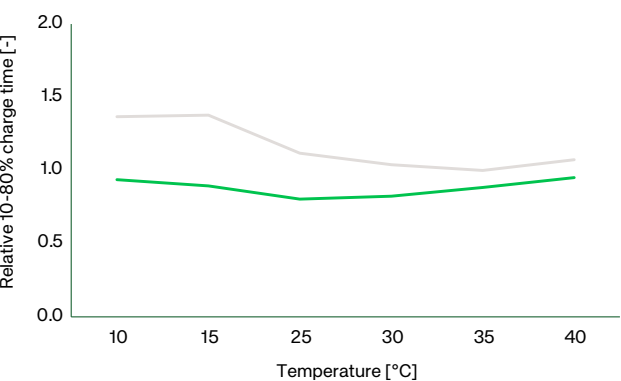
> **9000** DC charging events.

51% have a charging duration of 10-20 min.

33-73% average charging SoC interval.

47% charging events pre-conditioned.

Vehicle charge time improvements
in key 10-80% window



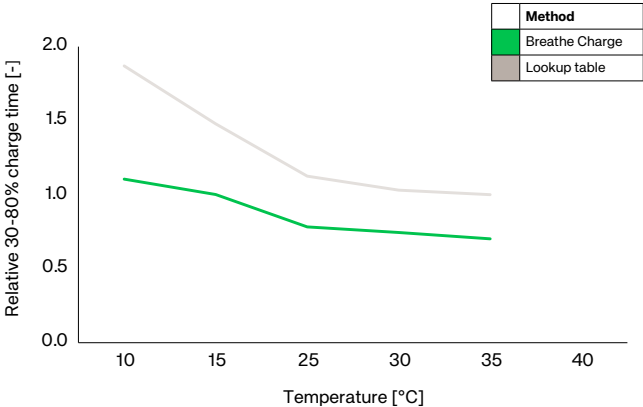
> KEY FINDING:

Vehicle level validation across a wide range of ambient temperatures and initial states of charge.

Improvements of more than **10%** were found in all cases.

Large performance gains at low temperature reduce the energy required for pre-conditioning.

Vehicle charge time is improved
across all use cases



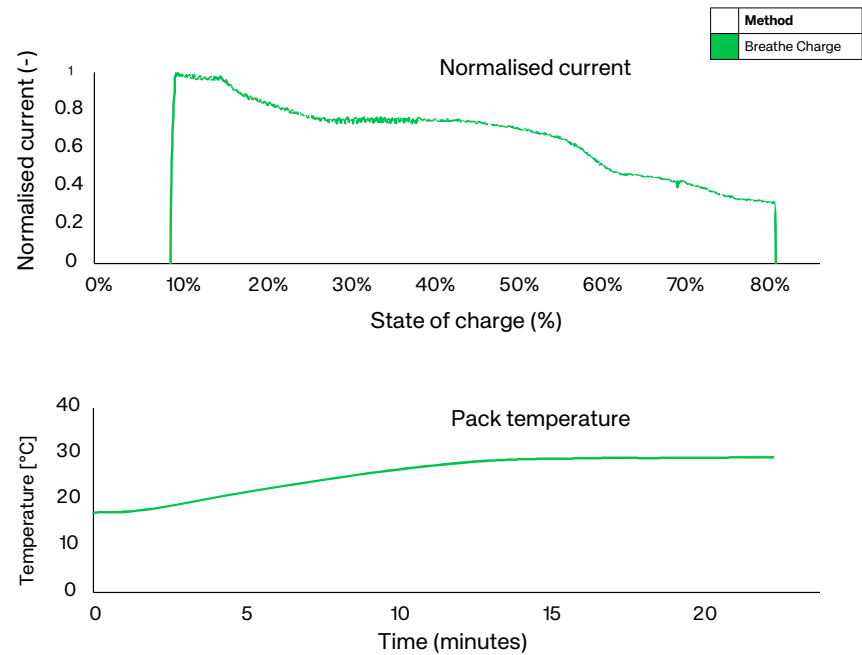
> KEY FINDING:

30% initial state of charge was found to be the “average” start of charge condition.

Vehicle performance improvements grow even larger away from the nominal **10-80%** case (>20% reductions).

Large improvements at low temperature are retained.

Vehicle validation example



> KEY FINDING:

Charging test performed at public charging station on prototype ES90 vehicle.

Ambient temperature -5°C and battery starting temperature +17°C.

Charging 10-80% SOC in ~21 mins: expected performance at optimal conditions is 20 mins.

Heating for at least 10°C battery temperature saves time and corresponds to several kWh of energy added.

Source: Model-based and Health-adaptive Charging of Electric Vehicles, Volvo Cars, EVS38.

Integration and deployment

> SYSTEM REQUIREMENTS:

Required inputs (needed at 1 Hz)

- Pack current
- Cell voltages
- Pack temperatures
- State of charge
- Auxiliary system limits
- Charge command (on/off)

Computational requirements

- Typical requirements for an 800V pack with over 100 instances of Breathe Charge:
 - **Automotive:** ~ 100 kB RAM, 200kB ROM, 0.5kB NVM, ~3ms compute time
 - **Consumer electronics:** ~ 10 kB RAM, 200 kB ROM, ~1ms compute time
- All memory is statically allocated
 - no dynamic memory is used.

AUTOSAR support?

- Yes

ASIL compliance level

- QM

ASPICE compliance

- ASPICE Capability Level 2

Software delivery formats

Delivered as a statically linked .lib or .a file, with header files and an integration API guide. Includes a calibration file for your specific cell and performance targets.

Implementation pathway

A typical engagement follows a structured pathway:

1. Model parameterisation:

Physics-based models are parameterised for your specific cell.

2. Margin calibration:

Simulation and empirical workflows to identify the margin required during fast charging.

3. Cell-level validation:

Validate performance at beginning of life, throughout ageing, and in various operating conditions (initial states of charge and temperatures). Conducted with both hardware-in-the-loop as well as in simulation.

4. BMS integration:

Partner to integrate Breathe Charge into your BMS firmware.

5. Vehicle integration:

Support pack-level and vehicle-level deployment.

The path forward

As energy density continues to rise to meet range expectations, delivering the fast charging experience drivers expect will come with ever-narrowing safety margins. The cost of imprecise control, in unrealised performance, customer dissatisfaction, and competitive disadvantage, will grow.

McKinsey's data confirms that range and charging speed are now table-stakes expectations. A third of prospective buyers expect charging in 20 minutes or less. Minimum acceptable range has risen to 500 km. And willingness to pay premiums is disappearing.

Leading OEMs will differentiate not only on chemistry, pack architecture, or thermal design, but on the precision with which they control internal electrochemical states during fast charging. Physics-based, closed-loop control is becoming essential infrastructure for next-generation EV platforms

> THE BOTTOM LINE

**HIGH-ENERGY BATTERIES DON'T LIMIT FAST CHARGING.
DEFENSIVE CONTROL DOES.**

Closed-loop margin control restores the performance that today's static safety margins force OEMs to give away, without compromising safety or durability.

Next steps

To explore how Breathe Charge can improve fast-charge performance on your platform:

- **Request a technical deep-dive** with our engineering team
- **Share cell data** for a preliminary performance assessment
- **Schedule a pilot programme** scoping discussion

> CONTACT

Tomas Juergensen

Product Manager - Breathe Charge

tomas.juergensen@breathebatteries.com

+44 (0) 7393 5575515

Breathe Battery Technologies
Office 7, 35-37 Ludgate Hill
London, EC4M 7JN
Registered in England and Wales
Company number: 11997339

