Battery State of Health & consumer transparency

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- *Limitations of onboard estimations*
- *Details on AVERE proposal for onboard capacity retention, including verification proposal*

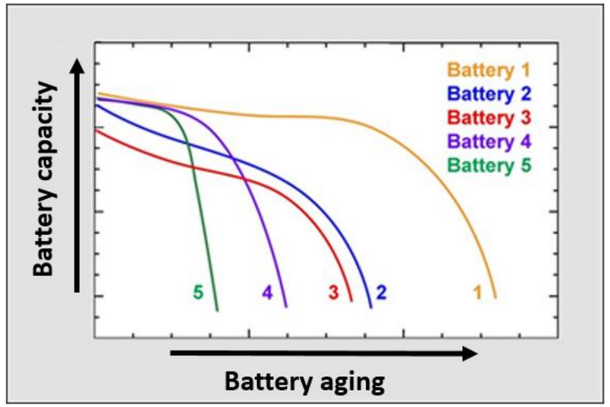
1. Introduction

Providing consumer transparency on battery aging for better EV uptake

Uncertainty around battery SOH slows down the transition towards zero-emission mobility

❖ Raises questions such as:

- How does a consumer buying a second hand EV know what they are buying?
- What about those buying for second life uses?
- How is a warranty claim for battery life verified?
- How do regulators prevent sub-standard EVs from entering the market?



https://batteryuniversity.com - Courtesy of the Dalhousie University

Consequences: EV residual values too low, monthly rates too high, obstacle to EV uptake

❖ Policy need: provide transparency on battery capacity retention for customer protection

Capacity loss has no impact on safety/health/environment: this is a consumer & market issue

v ICE vehicles' energy degradation / range over lifetime not regulated either

2. AVERE proposal on SOH

Using best metric to give free & reliable SOH information with most practical technical solution

Customers need insight into SOH in a way that:

- Provides relevant information on battery health that customers & interested market operators can easily access and understand
- Is accurate, transparent and verifiable so it can be trusted
- Is free for EV owners & can be activated by them whenever they want

It is also important that the **technical solution is practical.** It should be:

- Future-proof to apply to future EVs and cell chemistries
- Meaningful to the entire range of EVs
- Not add unnecessary costs
- Be easily verifiable

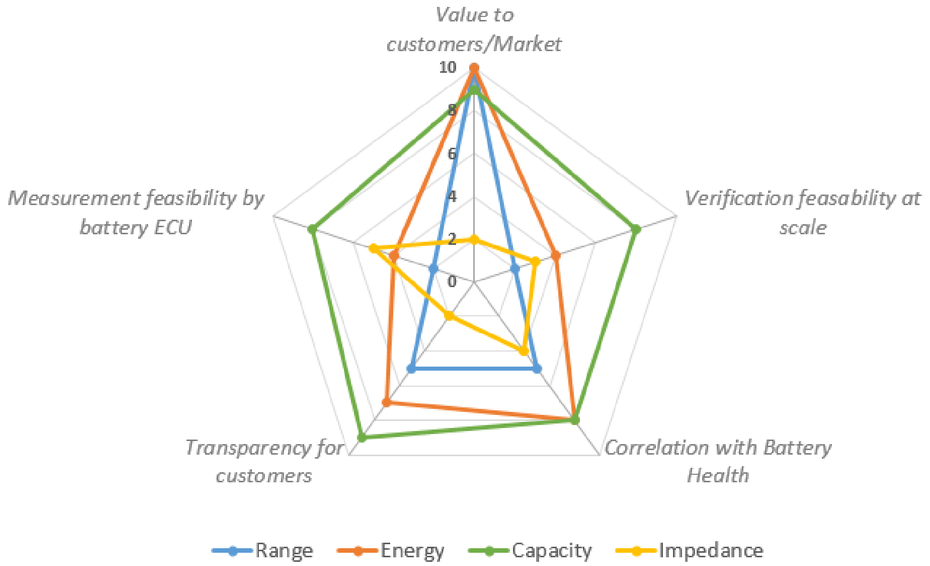
Criteria	Description
Value to customers	How valuable and useful is the metric to customers
Correlation with battery health	How indicative of battery health is the metric
Transparency to customer	Well defined metric with good accuracy
Validation/Verification feasibility at scale	How feasible is it to validate the accuracy of the metric in the field.
Measurement feasibility by battery ECU	Evaluates the feasibility of onboard computation of the metric for a given accuracy target.

2. AVERE proposal on SoH

Towards a common industry definition of SoH: capacity retention as best SoH metric

Using range, energy or impedance growth presents major flaws

- **Range:**
  - Too many factors impact transparency and precision of range retention calculation
  - Not a direct indication of battery health and not usable for standalone battery without vehicle-specific parameters
- **Energy:**
  - Available energy is a function of battery capacity, voltage, impedance and discharge load, so battery energy depends on application conditions and varies based on test temperature, discharge rate, etc.
  - Test procedure requires correctly following the discharge load: complex and possibly imprecise
- **Impedance growth:** Much less important than battery capacity loss as they relate to vehicle range, highly dependent on test conditions, hence single value can be misleading or inaccurate



Criteria	Metric proposal : grade [0-10]			
	Range	Energy	Capacity	Impedance
Value to customers/Market	10	10	9	2
Verification feasability at scale	2	4	8	3
Correlation with Battery Health	5	8	8	4
Transparency for customers	5	7	9	2
Measurement feasibility by battery ECU	2	4	8	5

2. AVERE proposal on SOH

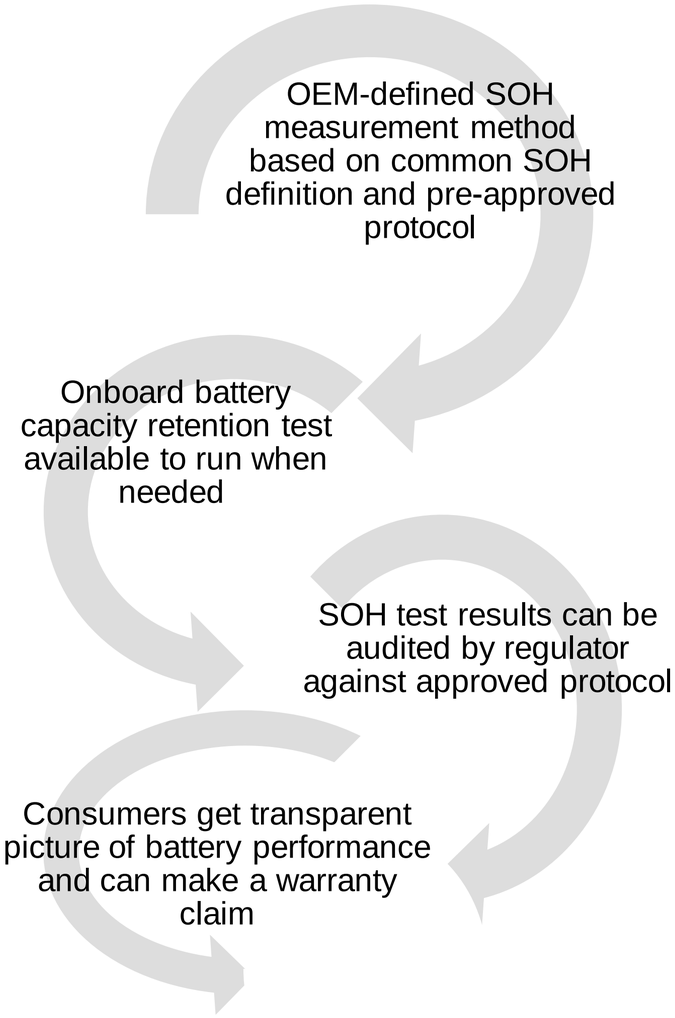
SOH estimation and verification

Common, clear definition of SOH and clear **pre-approved testing protocols:**

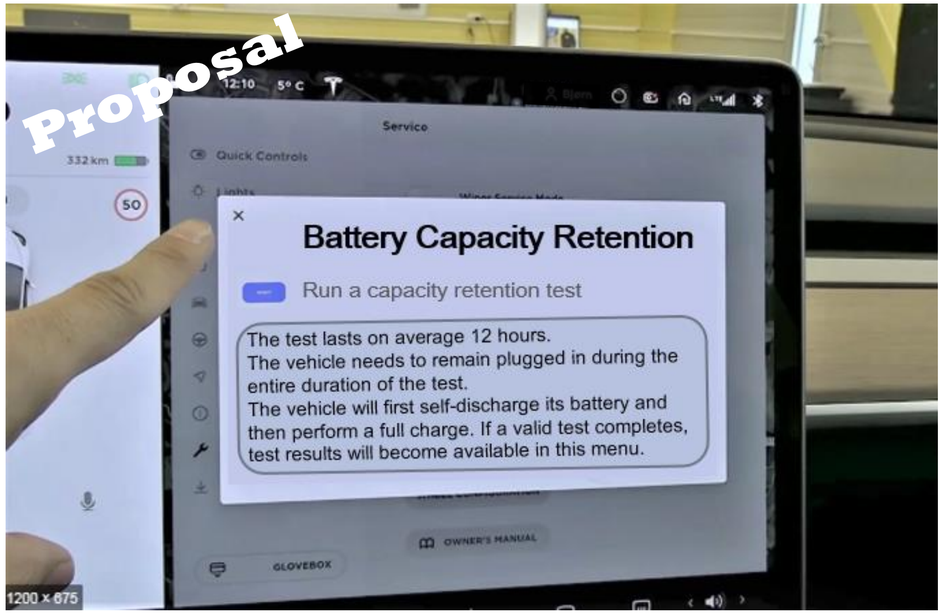
- ❖ SOH measurement should not be based on obscure algorithms
- ❖ Testing protocols would be defined by OEMs (cf AVERE proposal of onboard capacity retention test) approved by regulators to provide needed flexibility and allow for comparability
- ❖ OEMs' SOH results and test execution could then be audited by regulators against a pre-approved OEM SOH protocol. Any deviation would have a clear root cause.

Using SOH evaluation in best way for consumers:

- ❖ Verified, reliable and transparent SOH results based on regulator-approved SOH protocol
- ❖ Limiting divergences in estimations and allowing comparability
- ❖ Results are directly displayed and usable by customers to make a battery warranty claim.

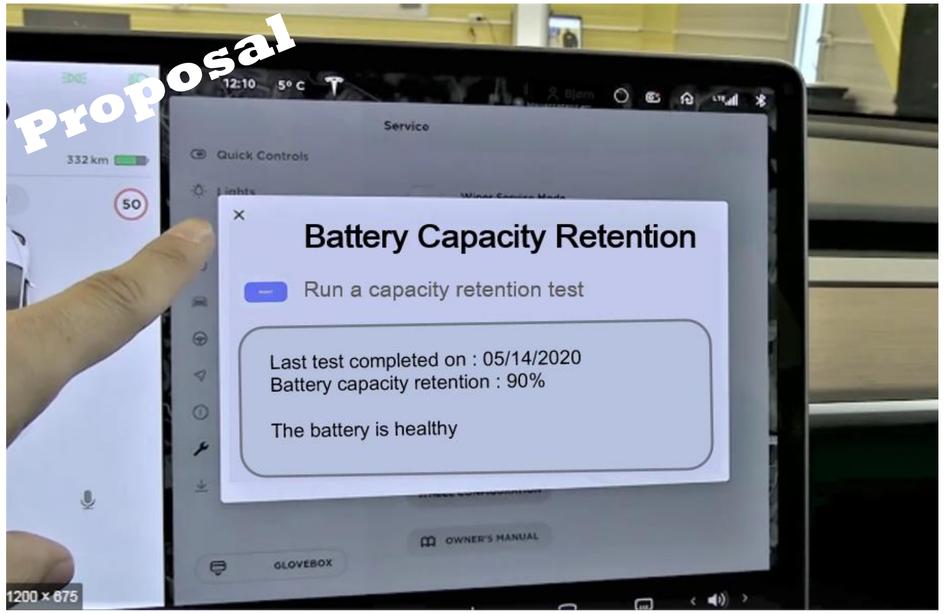


AVERE Proposal



A

B



- Customer can initiate a battery capacity test via the vehicle's user interface. The vehicle will automatically run the test procedure.

- Method A: Full discharge followed by a full charge
- Method B: Full charge followed by a full discharge

- The vehicle can automatically pick the ideal test method based on initial conditions, but user can override

✓ Reach Full Discharge

✓ Measure capacity during full charge

✓ Process results

- If a successful capacity test completes, results become available on the user interface

- This provides clear and trustworthy information to the customer

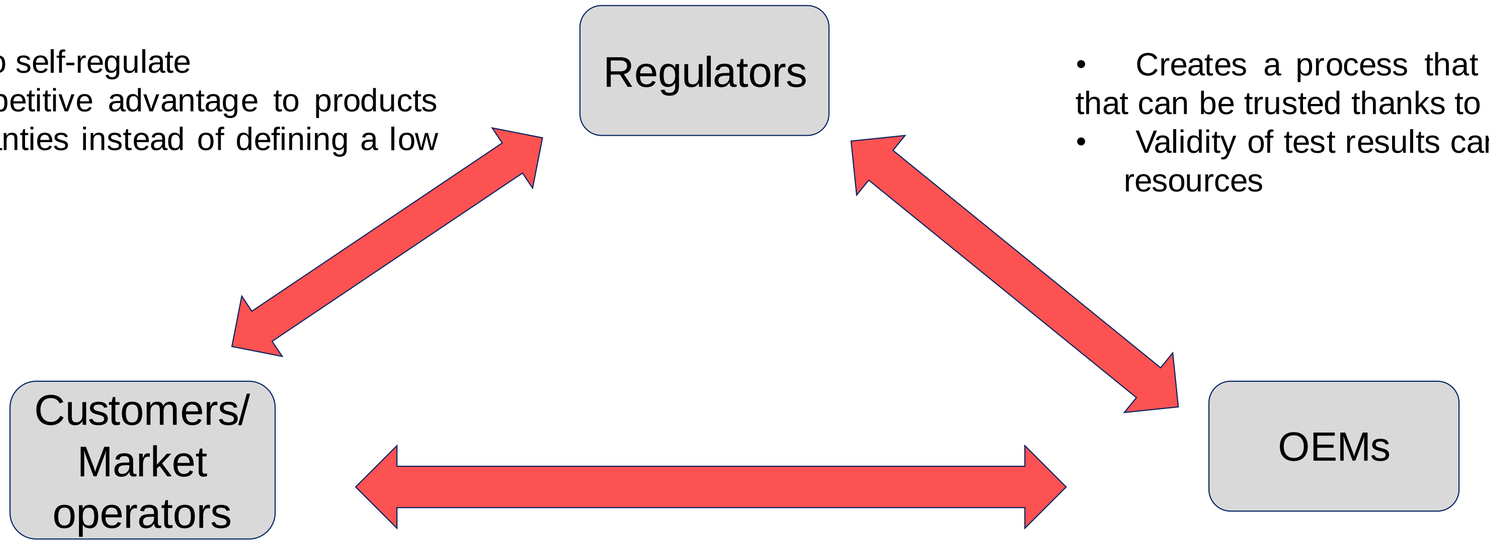
- Becomes a solution to handle warranty claims in a fair, clear and efficient fashion

2. AVERE proposal on SOH

Roles and responsibilities to communicate on SOH for better consumer transparency

- Define requirements for reported capacity retention diagnostic :
  - Accuracy target
  - Way to report results : resolution of report, OBD/dashboard, etc.
- Reviews and approves OEM's SOH protocol.
- Check that published protocols are correctly followed and deliver results that meet accuracy targets

- Allows market to self-regulate
- Creates a competitive advantage to products with better warranties instead of defining a low bar.



- Creates a process that provides valuable information that can be trusted thanks to clear test protocols.
- Validity of test results can easily be verified with limited resources

- Can request battery capacity retention tests directly via the User Interface
- Can access test results to assess their EV battery health
- Can use capacity retention test results for warranty claims, and advertising of 2nd hand / EoL products

- Define details for their own test protocols to deliver capacity measurements within tolerance for their products
- Define nominal capacity of their products
- Do what is necessary to enable capacity checks on their products and report results as specified by regulators

3. AVERE proposal obviates the need for additional regulations

- AVERE proposal, in combination with manufacturer SoH warranty, will create market transparency and competition for battery performance (like other aspects of vehicle reliability)
- It is possible to do a SoH check just before the battery reaches EoL in the vehicle for potential second use
- With the customer protected, the cost of poorly performing batteries is internalised with the OEM. Warranty applies regardless of fast charging, temperatures, racing, …. This is regular business risk
- This obviates the need for:
  - Ex-ante MPRs
  - Testing of range retention
  - SoH testing during roadworthiness checks
  - Separate regulations for second-life SoH checks

3. Unintended negative side effects of a battery MPR

Leads to batteries with harmful 'spare capacity'

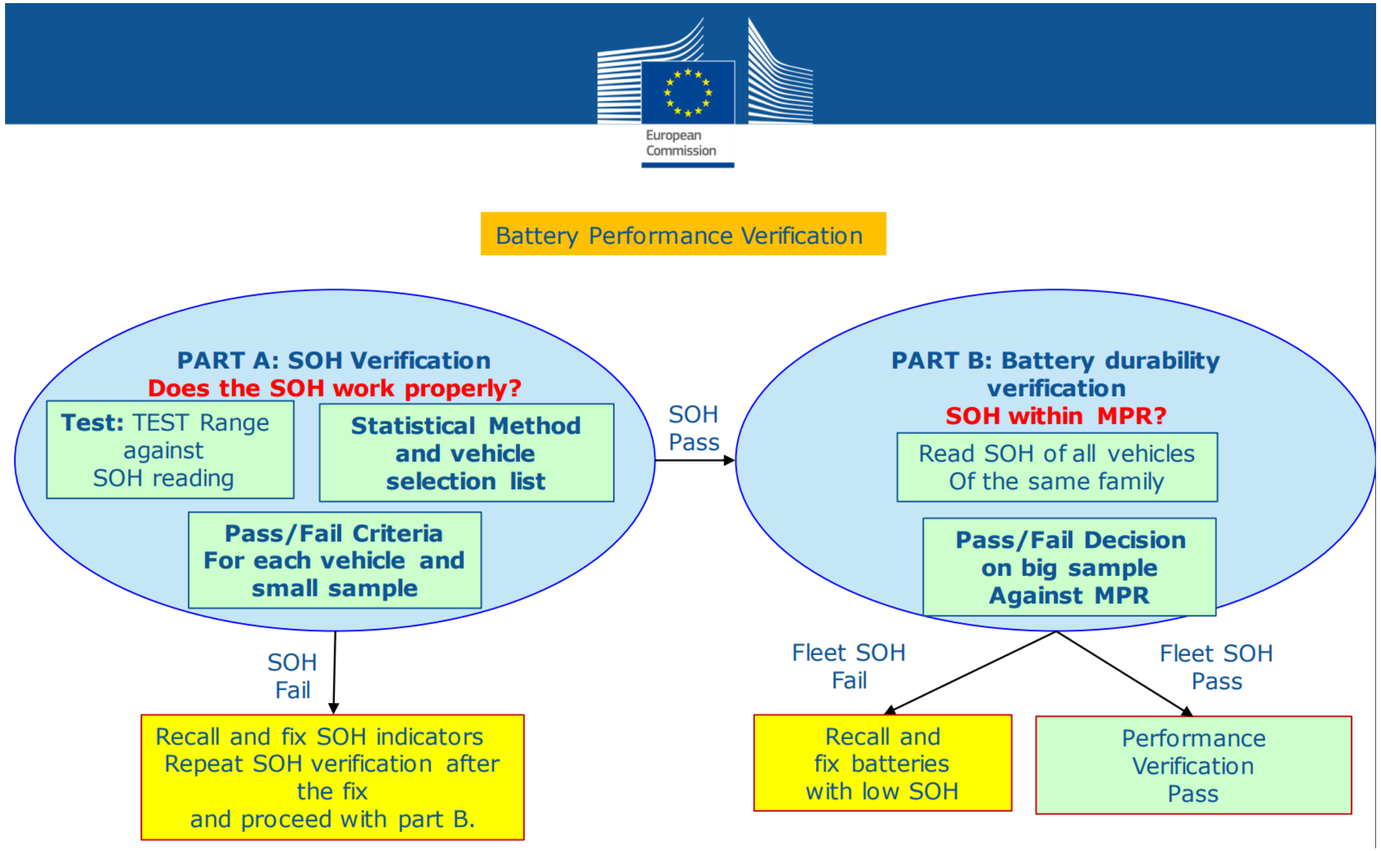
- In case the MPR is challenging, OEMs will add additional spare capacity - that won't be available to the customer - to the battery to meet the MPR.
- This increases the environmental footprint of batteries, adds mass and increases vehicle energy consumption, and increase product costs; all of which will slow the transition towards zero-emission transport

Distorts markets

- For a 150 km EV, 70% retention means substantial loss of utility; but a 1,000 km EV with 50% retention is still very functional. Performance objectives may be arbitrary in that context.
- Customers should still be able to purchase a product that has limited retention warranty/capability; not everyone has the same retention expectation.
- In case the MPR is not challenging, the perceived quality of EVs can be negatively impacted

4. Comments on latest Commission proposal

Especially on range check and MPRs



Part A: AVERE supports OEM choice in how SOH is measured, using the best possible SOH metric and protocol (capacity retention)

However, we see major challenges with the 'range check':

- This introduces many non-battery variables that are not regulated with ICE vehicles
- Confusion with battery retention warranty claims: what to do if SOH test indicates a 'pass', but range a 'fail' ?
- Check of SOH methodology should be based on battery capacity retention like the OEM test, not on range

Part B of the proposal is not needed if Part A is executed well, because customers can get new battery under warranty.
Again, this is not a safety/health/environmental issue, it is a consumer quality and information issue and should be treated as such

5. Intermediate conclusions

Addressing uncertainty in EV battery deterioration accelerates the transition towards zero-emission transport:

- Market: it increases residual values (hence lowers monthly costs)
- Customer: It provides him/her with the tool to claim warranty
- OEMs: It deters OEMs from bringing sub-standard vehicles to market

An effective, practical solution:

- provides SoH information that can be used in warranty claims
- imposes no additional burdens on EV owners: they can do the test anytime, without involvement of third parties, at no cost (other than the electricity used for the test)
- uses battery capacity retention as a metric, in a context where there are complex dependencies between pack and vehicle

AVERE proposes an onboard SoH check based on capacity retention that fulfils these criteria

Regulators to define parameters of the SoH check, validate OEM protocols, and validate in use performance

This proposal obviates the need for additional regulations e.g. MPRs, range testing

Appendix

Overview

Technical background: battery pack key characteristics, factors impacting EV range

Selected criteria to define best SOH metric

Limitations of onboard estimations

Details on **AVERE proposal for onboard capacity retention, incl verification proposal**

Technical background

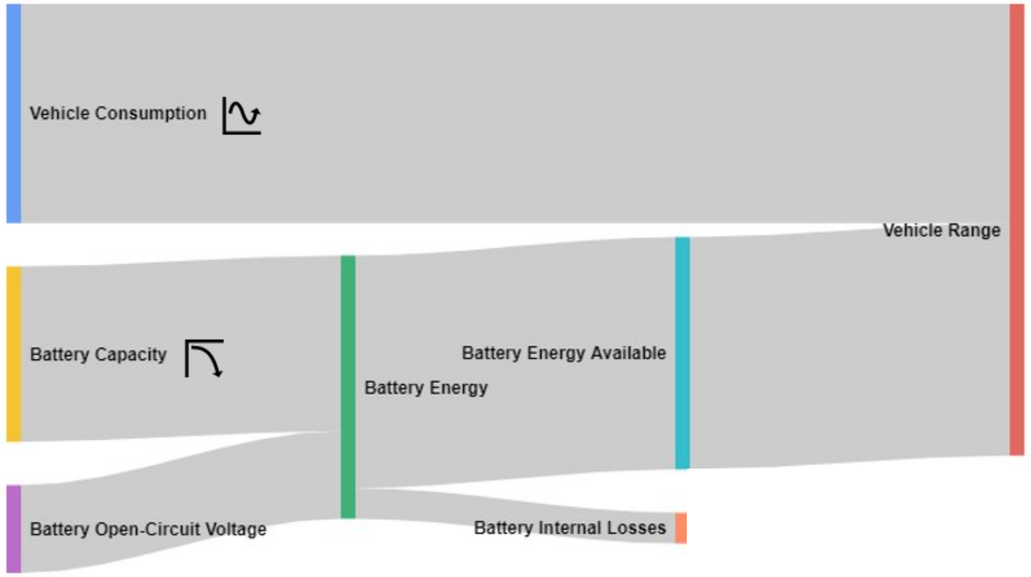
Battery Pack key characteristics:

- ✓ **Capacity [Amp-hours]:** Total amount of electric charge that can be delivered from full to empty.
  - Very low deviation across test conditions : Charge vs Discharge, rate, temperature, etc.
  - Decreases over battery aging
- ✓ **Open-Circuit Voltage [V]:** Voltage of the battery under no load.
  - Depends on State of Charge and is a characteristic of the chemistry of the cells.
  - Typically low deviation over aging
- ✓ **Impedance [Ohm]:** Resistance to charge flow within the pack
  - Typically increases over aging with dependencies of State of Charge and Temperature
- ✓ **Energy [Watt-hours]:** Total amount of work that can be delivered by the battery
  - Depends on discharge conditions (load, temperature)
- ✓ **Power capability [Watt]:** Rate of energy flow that the battery can deliver (discharge) or accept (charge)
  - Depends mainly on battery voltage and internal impedance.
  - Battery is not always the limiting component for vehicle power capability (ex: charge cables, electric motor, etc.)

Vehicle range is the combination of vehicle consumption under a given drive profile and the amount of energy that the battery can deliver.

This amount of energy available depends on several key battery characteristics with different importance and evolution over battery aging.

Quantitative visualization of factors that impact EV range



A Tesla on a chassis dyno

Official range testing does require a full drive down to measure battery *energy*. It is a complex process prone to mistakes that can take days to complete. Capacity test procedures are much simpler.

How should SOH be defined?

- In order to find the best metric for SOH we defined the following criterion:

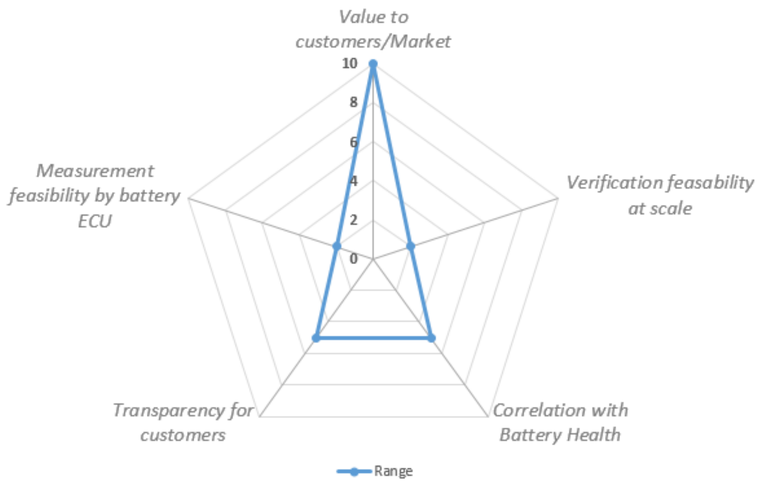
Criteria	Description
Value to customers	How valuable and useful is the metric to customers
Correlation with battery health	How indicative of battery health is the metric
Transparency to customer	Well defined metric with good accuracy
Validation/Verification feasibility at scale	How feasible is it to validate the accuracy of the metric in the field.
Measurement feasibility by battery ECU	Evaluates the feasibility of onboard computation of the metric for a given accuracy target.

- We narrowed down the selection of metrics to the following ones:
  - Range [Range retention]
  - Energy [Energy retention]
  - Capacity [Capacity retention]
  - Impedance [Impedance growth]

- For each metric, review the different criterion and assign a grade from 0 (bad) to 10 (great)

What metric should define SOH ?

Criteria	Evaluation [0-10] for the metric : Range retention
Value to customers/Market	10
Verification feasability at scale	2
Correlation with Battery Health	5
Transparency for customers	5
Measurement feasibility by battery ECU	2



Metric : Range retention

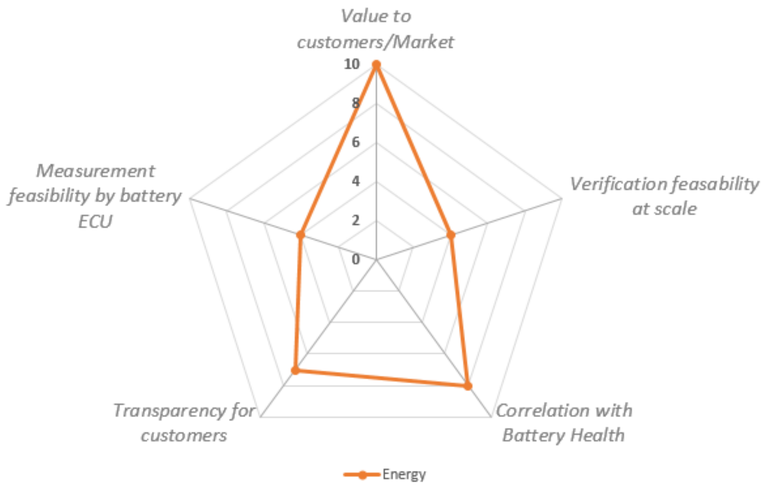
- The **measurement of a vehicle range** is the result of a **complex and lengthy process** that is necessary in order to correctly capture the **different factors at play**

- From a customer standpoint, the idea of knowing the range retention of an EV vehicle appears **valuable**. The **apparent simplicity** of this metric unfortunately hides several shortcomings, mainly because it **depends on many factors external to the battery system**.
  - Range retention is **not a direct indication of battery health**
  - The high number of factors defining vehicle range **negatively impact the transparency of this metric**. (ex: Efficiency can improve thanks to software controlling vehicle behavior, by example motor control. Also, efficiency can be reduced by components outside of the battery system like tires, clutch, etc.)
  - A **standalone battery** would **not be able to report a range retention metric** as parameters specific to the vehicle using the battery are required.

- The large number of factors impacting range retention calculation significantly **reduces the precision** of the metric and increases the **difficulty to root cause discrepancies** between reported and actual values.

What metric should define SOH ?

Criteria	Evaluation [0-10] for the metric : Energy retention
Value to customers/Market	10
Verification feasability at scale	4
Correlation with Battery Health	8
Transparency for customers	7
Measurement feasibility by battery ECU	4

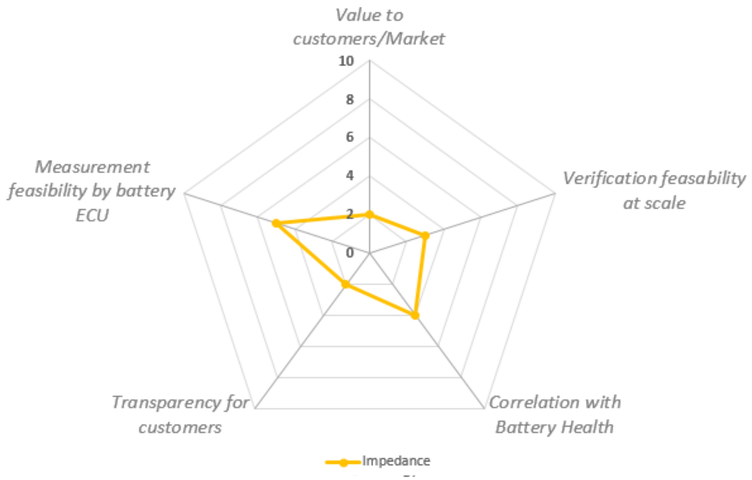


Metric : Energy retention

- **Energy** is the battery characteristic that relates the most directly to vehicle range.
- Energy available is a function of battery capacity, voltage, impedance and discharge load. Therefore, battery energy depends on the application conditions and varies based on test temperature, discharge rate, etc.
- Internal losses increase with the square of the load. For a given drive cycle, battery load depends on the vehicle consumption. It is increasingly common for OEMs to use a given powertrain as a platform for different vehicles that can have significant consumption delta. The fact that energy depends on the discharge load has several consequences:
  - A **standalone battery** would **not be able to report an energy retention metric** as parameters specific to the vehicle using the battery are required.
  - Measuring the actual energy of aged packs requires a test procedure that correctly follows the discharge load, which adds complexity.
  - Complexities for the battery ECU to accurately compute the metric and therefore reduces the precision of the metric.

What metric should define SOH ?

Criteria	Evaluation [0-10] for the metric : Impedance growth
Value to customers/Market	2
Verification feasability at scale	3
Correlation with Battery Health	4
Transparency for customers	2
Measurement feasibility by battery ECU	5

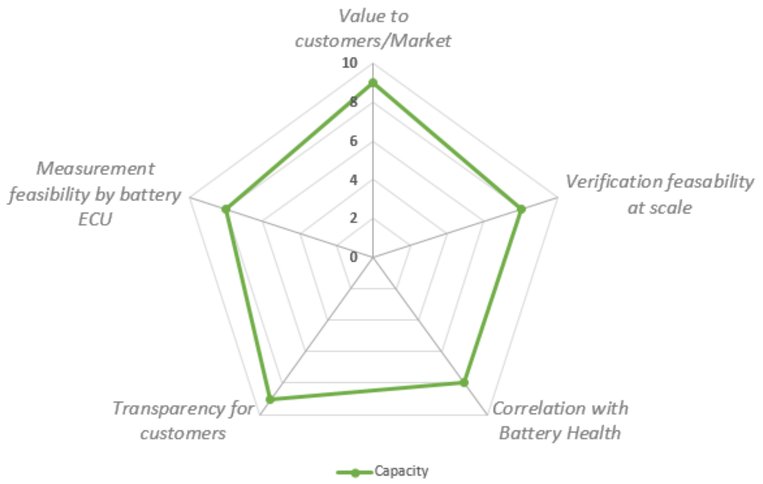


Metric : Impedance growth

- Impedance reduces the energy available to the vehicle, but this inefficiency is generally a small fraction of delivered energy and therefore ***impedance growth is much less important than capacity loss as they relate to vehicle range*** over time.
- Like capacity, internal impedance changes over the life of a battery as well. However, this parameter strongly depends on temperature, State-Of-Charge (SOC) and time horizon.
- Therefore impedance, and impedance growth are highly dependent on test conditions. It can be misleading and inaccurate to reduce impedance growth to a single number.
- Impedance growth can also impact maximum battery power capability. This is a second order effect and the battery is not necessarily the component limiting charge or discharge power in a vehicle.
- Overall, knowing impedance growth doesn't provide much value to the customer.

What metric should define SOH ?

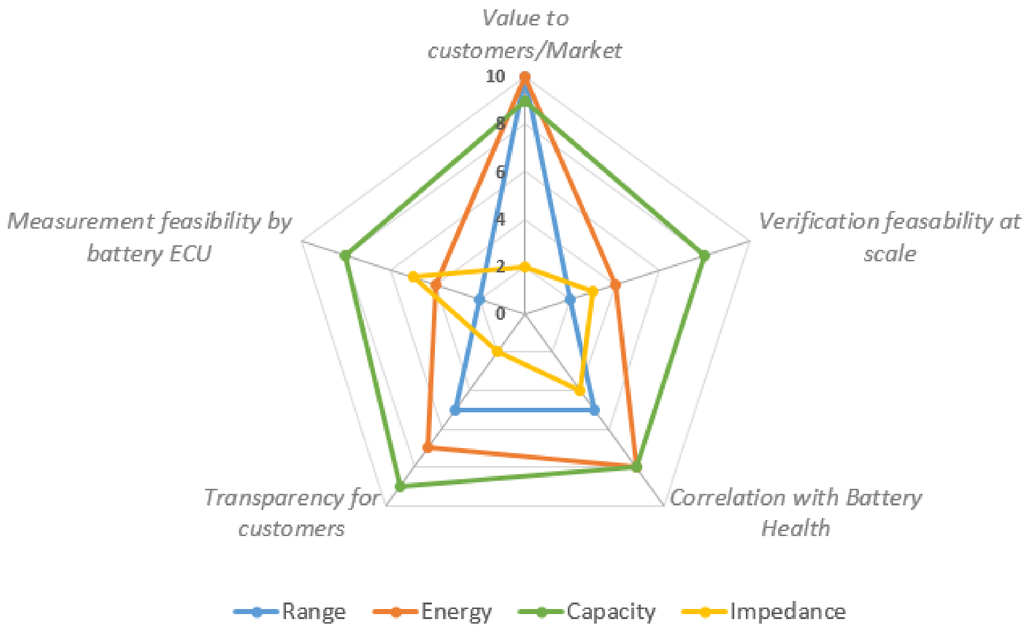
Criteria	Evaluation [0-10] for the metric : Capacity retention
Value to customers/Market	9
Verification feasability at scale	8
Correlation with Battery Health	8
Transparency for customers	9
Measurement feasibility by battery ECU	8



Metric : Capacity retention

- Battery capacity **is directly proportional to vehicle range**.
- This metric is the one that depends the least on test conditions (Discharge vs Charge capacity, Charge/Discharge rate, temperature, etc.)
- Capacity can be easily run with an onboard diagnostic procedure which discharges and charges the battery with little conditioning.
- Capacity estimates **can be verified with simple measurement equipment**

What should define SOH ?

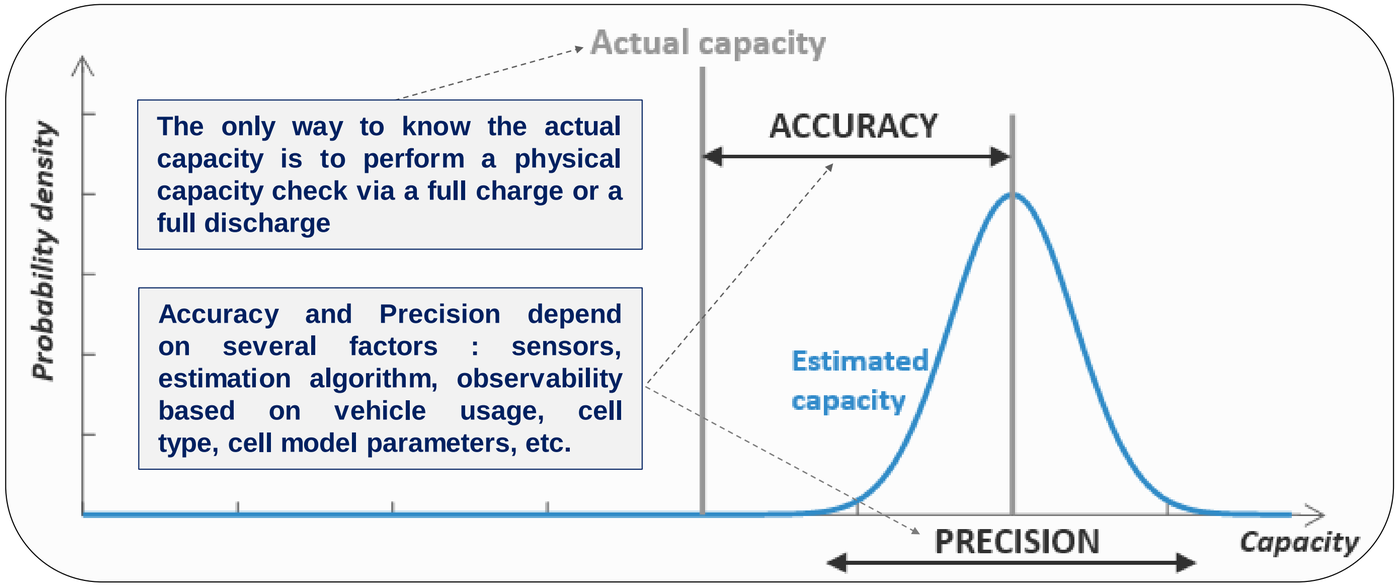


Criteria	Metric proposal : grade [0-10]			
	Range	Energy	Capacity	Impedance
Value to customers/Market	10	10	9	2
Verification feasability at scale	2	4	8	3
Correlation with Battery Health	5	8	8	4
Transparency for customers	5	7	9	2
Measurement feasibility by battery ECU	2	4	8	5

Capacity retention is the most feasible SOH metric

Onboard capacity estimation

Most Battery Management Systems estimate remaining capacity onboard using various methods. The estimation comes with a potential error that depends on a combination of many different factors.



Facts:

- Most capacity estimation techniques only use the information available opportunistically - accuracy varies vehicle to vehicle.
- Onboard, battery capacity is typically only partially observable: EVs rarely perform full charge/discharge cycles
- For a given vehicle, estimation accuracy can drastically change over time due to vehicle usage change, various cell parameter changes, sensor calibration, etc.
- Estimation accuracy can have a direct impact on product cost.

Most OEMs use in situ, onboard capacity estimation that can vary in accuracy based on many factors. Proprietary algorithms are used to handle inaccuracies and output an estimate that can be consumed by other ECU algorithms. Onboard capacity estimation is not necessary designed as diagnostic signal.

Limitations of onboard capacity estimation

- Most OEMs use in situ, **onboard capacity estimation that can vary in accuracy based on many factors**. Proprietary algorithms are used to handle inaccuracies and to output estimates that can be consumed by other ECU algorithms. **Onboard capacity estimation is not designed as continuous diagnostics signal**.

- **Aggregation** of individual estimates **at the fleet level** can provide valuable insights, sometimes highlighting **trends due to algorithm error** under given conditions **rather than actual battery degradation trends**.

- **Observability of battery capacity** strongly **depends on the usage of the battery**. For example when a **vehicle is not used** (its battery is not cycled), **capacity cannot be observed**, while **actual capacity may degrade**.

- **Onboard estimates** are **not suited to be used as a pass/fail performance criteria**.

- **Verifying the accuracy** of a product's capacity estimation by a third party **would require significant efforts**:

    - It would be necessary to perform a very large number of tests in order to verify the metric's compliance. Statistical sampling is only possible ex post.
    - Onboard estimation algorithms can be updated over time. Such a change would invalidate any verification dataset collected before the update.
    - Estimation algorithms often rely on cell model parameters that can evolve over cell aging. As a result it is not possible to verify the performance of estimation algorithms on aged cells until representative aged packs become available.

Making rules relying on situ onboard capacity estimation is fraught with challenges for OEMs and regulators. A better solution would be to rely on physical measurements of battery capacity.

VERIFICATION OF CAPACITY DIAGNOSTIC TEST

- Verification Proposal:
  - X vehicles sampled and diagnostic test run
  - OEM provides rated Beginning of Life (BoL) capacity
  - Full drive down on dynamometer from maximum charge mode to vehicle shut down on Shortened Type 1 test procedure. Similar procedure for range test.
  - New vehicles shall not measure Y% greater Amp-hours than rated BoL capacity
  - Used vehicles shall be within Z% of diagnostic test retention based on measured amp-hours and BoL capacity at any point in A years or B km