WHITE PAPER

Battery State of Health (SoH): The Powerhouse Behind the Battery Passport

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Overview

High power lithium-ion batteries are a key part of a clean energy future, providing temporary storage for renewable energy, and for powering electric vehicles. Lifecycle management, ensuring sustainability of the battery supply chain and a circular economy for critical battery minerals, are paramount for supporting this vision.

In 2016, the World Economic Forum launched the Global Battery Alliance (GBA) to establish a sustainable battery value chain by 2030. In initiating its work, the GBA conceived of a digital twin for batteries, called a battery passport. The purpose of the battery passport is to support sharing of battery supply chain data and information about what happens to a battery during its lifetime to ensure responsible environmental, social and governance aspects in the supply chain, and recovery and reuse of battery materials once it reaches end of life.

In 2023, to support this and to provide common standards across the EU market, the European (EU) Battery Regulation (Regulation 2023/1542) was approved by the European Council, with a requirement for all new electric vehicle (EV) and industrial batteries (over 2 kWh) in the EU market to have a unique battery passport by 1st February, 2027. Following on from the EU Battery Regulation, other regions, including China and the USA, are developing their own versions of the battery passport.

To fully assess the EU Battery Regulation, and to advise and prepare stakeholders, the German government and the European Commission established The German Battery Pass Consortium (the Battery Pass). The Battery Pass provides comprehensive guidelines on all aspects of the battery passport for securely sharing information along the battery value chain in accordance with the EU Battery Regulation.

In the Battery Pass content guidance document “Battery Passport: Data Attribute Longlist”, there are a number of categories that specify attributes for inclusion in the battery passport. In the Performance and Durability category several of these attributes relate to battery State of Health (SoH).

This paper examines why battery SoH is critical for safe and effective lifecycle management of electric vehicle and energy storage batteries, to which stakeholders it applies, and the newest technological innovation that makes producing and sharing this data with all these stakeholders, and thus regulatory compliance, seamless.

What is battery State of Health?

A new battery ideally has a SoH at 100 % of its specification, and this decreases over time as conditions, such as environment, usage, and recharging patterns, contribute to the chemical and physical degradation of the battery cells. SoH is essentially a measure of the performance capability of the battery at a given time compared to its performance capability when it was new.

SoH is, therefore, an important indicator of its condition at any point in its lifecycle and is used to determine remaining battery longevity and reliability. For example, while the battery is in the vehicle, the SoH will be used in part to calculate the predicted total range available. Some EV's also provide SoH as a percentage for owners or service personnel to view within the infotainment menu options, or via a smartphone app, which can be useful in a variety of ways, such as whether a warranty claim needs to be made, or whether the battery should be replaced.

Which standard is used to define battery State of Health?

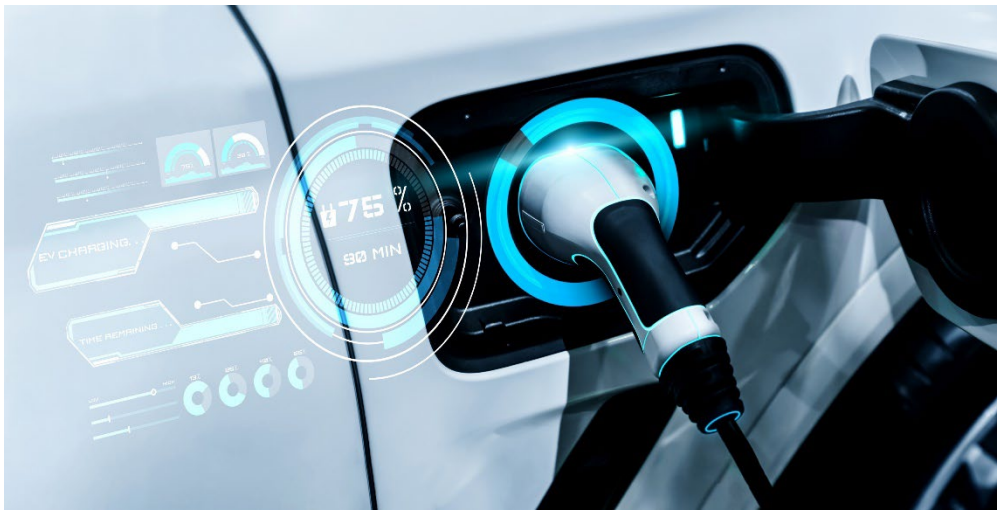
The SoH of a battery is not a quantity that can be measured directly and there is no consensus on how to determine it. A variety of methodologies are regularly proposed, all of which fundamentally require the measurement of one or more physical parameters, such as internal resistance, capacity, voltage, and temperature, which are then used in models to estimate the SoH. Therefore, instead of recording a simple SoH value, the most commonly used parameters to determine SoH are required attributes of the battery passport.

For instance, in the Battery Passport Data Attribute Long List, the Performance and Durability, Capacity, Energy, SoH, and Voltage subcategory requires ten attributes to be recorded including three related to energy, three related to capacity, three related to voltage, and one related to charge.

Why is recording battery State of Health in the Battery Passport important?

While the battery is in use, for example in an EV, SoH can be read directly, or parameters can be measured and SoH calculated. Further information may also be accessible through the diagnostic systems available to some certified mechanics. However, when the EV is retired, things get especially difficult. If the vehicle cannot be turned on, or if the battery has already been removed, determining the SoH could become a lengthy, manual charge and discharge procedure.

Therefore, to improve the safety and viability of reuse or recycling of retired batteries a faster, easier method of determining the battery SoH is needed. The recorded SoH attributes in the battery passport can be used to quickly determine SoH at the time that the attributes were recorded. This would avoid the need for the safe working environment and specific equipment required to charge and discharge the battery.



To whom is battery State of Health important?

Everyone directly or indirectly associated with each stage of the battery's lifecycle can benefit from knowledge of the battery's SoH. This includes consumers, battery manufacturers, OEMs, service garages, transporters, insurers, refurbishers (for next-life repurposing), and recyclers. The reasons why SoH data is important to some of these stakeholders are described below.

Consumers

How a battery is used can affect battery health and longevity. For example, if an EV owner repeatedly drives down the battery to just above zero range, frequent recharging from low to full charge, and especially the use of fast charging, can contribute to degradation. For these consumers, having access to SoH information can inform them of better charging practices.

In addition, SoH can be used more accurately to estimate range and communicate potential battery faults. If the owner observes unexpected EV battery degradation when their driving and charging practices have been good, SoH can inform the owner of when a replacement battery would be required, or potentially covered under warranty.

Battery passports can also benefit consumers in purchasing decisions. When it comes to buying a second-hand EV, seeing the battery's current SoH gives a more accurate indicator of the vehicle's worth, supporting the buyer's decision-making process.

OEMs

While battery SoH ensures OEMs meet the EU Battery Regulations, it is also beneficial for business reasons too. When the vehicle is brought to a dealership garage for servicing, the technician can compare SoH percentage vs. previous readings and the time in between. If the battery seems to be degrading more quickly than usual, the technician can further inspect for failures and/or advise the owner how to better their charging practices. SoH information can also determine whether a faulty battery is eligible to be replaced under warranty or whether the

warranty was voided due to poor charging or use practices; such as leaving the vehicle for a period at or near zero State of Charge (SoC) or exposure to very high or low ambient temperatures.

Transporters

Electric vehicle and licensed battery transporters have far fewer resources for determining battery SoH than many others. Their job is to retrieve the EV or battery, or transport it from point A to point B, including having the proper permits, completion of required paperwork, and hazard placards as required.

When the item being transported is new, the transporters will have a higher level of confidence in the safety of the operation. Once the EVs or batteries reach the end of their first life and are in better condition than expected, this can potentially be used to negotiate reduced insurance and shipping costs. However, after an accident, or if the batteries have not been serviced for some time, the SoH of the battery can help the transport owner to determine the risks involved in transporting the batteries, or vehicles, and ensure that mitigation measures are in place to prevent or control any safety-related issues that might be encountered during transport.

Insurers

The fate of most vehicles involved in accidents is usually determined by the company insuring the vehicle. When the insurance claims adjuster determines that the repair value exceeds the vehicle value, they will not repair it and will tell the customer to where it needs to be towed for further processing. If the insurer can gain a quick understanding of the battery SoH, more informed decisions can be made on where to tow the vehicle to, and how to safely tow it.

If the vehicle must be scrapped, determining the state of the battery after an accident is critically important, since it is the most valuable component. The SoH reading can help to determine if the battery is worth reusing in another application, or whether recycling is the best option.

Battery refurbishers, repurposers, and recyclers

Even though battery manufacturing capacity is predicted to reach between 4.7 TWhr[1] to >5 TWhr[2] by 2030, the scarcity of minerals used for cell manufacturing is one of the drivers of the World Economic Forum's goal of achieving a sustainable battery supply chain. Extending the life of batteries and ensuring domestic recovery of battery materials has therefore become paramount. For EV battery refurbishing, repurposing, and recycling operations, having quick access to battery SoH data enables these stakeholders to make quicker, more cost-effective assessments of batteries prior to receiving them.

[1] Battery 2030: Resilient, silent, sustainable and circular – McKinsey & Co.
[2] Battery recycling takes the driver's seat – McKinsey & Co.

Transporting batteries is a costly and potentially hazardous business. Ensuring that batteries are suitable for refurbishment or reuse, and minimizing transport risk and cost, is vitally important. In 2021, a US based battery repurposing operation reported that 40% of the batteries received for repurposing were not suitable, requiring transportation off-site. That not only adds tremendous cost but also creates a huge carbon footprint in the very industry tasked with reducing CO_2 emissions. Conversely, a battery recycler does not want to recycle a battery that is suitable for reuse. Although recycling EV batteries produce materials of value, the reuse value, both economically and environmentally, is significantly higher.

With ready access to battery SoH information, these key players in the battery lifecycle can assess the battery prior to providing pricing or agreeing to accept a battery for processing.

Producing battery SoH data - Challenges and solutions

Most EVs are designed with a battery management system (BMS) that actively monitors the battery through sensors placed throughout the battery packs including voltage, current and temperature, determines essential information, such as the SoC or SoH, and calculates the remaining range for the driver. The BMS monitoring ensures the battery is operating within the prescribed limits; if that is not the case, then the BMS will trigger a number of actions to solve the problems, such as managing the cooling system if the pack or cells get too hot, or balancing the cells to make sure they are all operating at the same voltage level.

What the BMS cannot do

The BMS can only work if connected to an external power source, for example the 12/48 V battery in an EV, so when disconnected no data is available. Only if a recycler or repurposer receives a complete battery pack and has the specific tools required, can they power it up with the appropriate power source and read any stored data. If modules or cells are disassembled from the battery pack, they are no longer connected to the BMS, and therefore are no longer being monitored. If a battery refurbisher or repurposer wants to analyze the SoH of a module or cell, specialized test equipment and time is required to, for example, run charge and discharge cycles.

Next generation battery State of Health: Cell-level monitoring for increased safety, regulatory compliance, and enabling the circular economy

Instead of being restricted to the BMS and the battery as a whole, Dukosi's method of reading and recording data for SoH calculations is different. Its unique chip-on-cell technology means that a DK8102 Cell Monitor chip is attached to each cell in the battery. Parameters such as cell voltage and temperature, that can be used in calculations to determine the SoH of each cell, are measured and analyzed, providing accurate, real-time, synchronized operating data. In addition, each cell's data is recorded directly in its respective Cell Monitor's permanent storage, retaining lifetime data and event logging, thus making a cell passport for each cell that stays with that cell, even if it is removed from the original battery and BMS, and repurposed elsewhere.

In addition, because the DK8102 Cell Monitor is attached directly to the cell, and is powered by the cell, parameters continue to be measured and recorded even when the battery has been removed from the application. This means that any SoH determination from the parameter data is completely up to date, compared to other approaches, where the data could be somewhat out of date if the battery has been sitting in storage and exposed to harmful temperatures.

This on-cell approach goes beyond the requirements of the European and US Battery Passport regulations, while also providing several further benefits to battery builders, operators, and second-use applications in a circular economy.

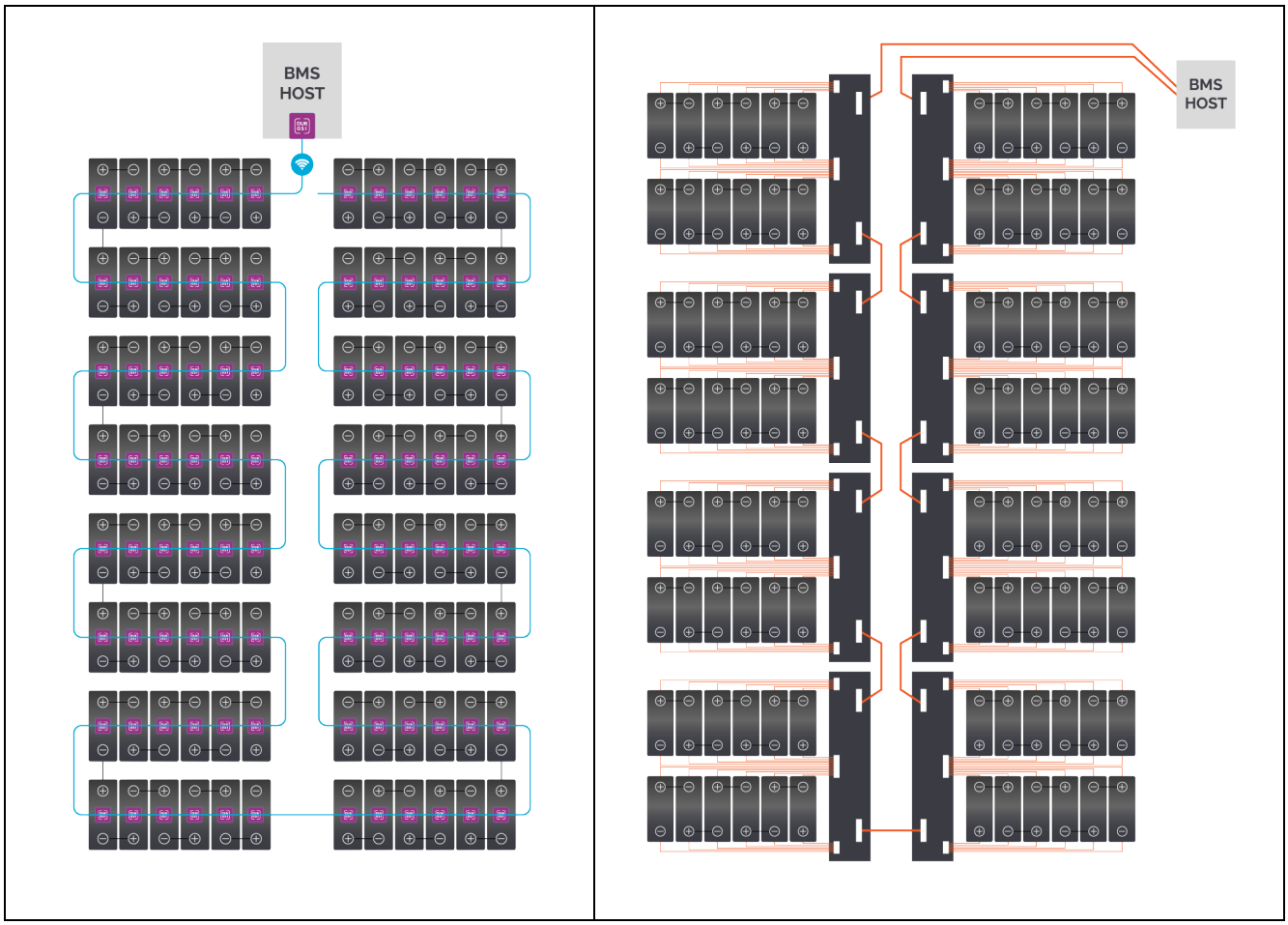
Each DK8102 Cell Monitor connects to a DK8202 System Hub, which is located on the PCB of the main BMS controller. Up to 216 Cell Monitors can form a network, ensuring even the largest battery capacities can be accommodated. The inherently electrically isolated, contactless communication between the Cell Monitors and System Hub is enabled by a bus antenna and defined by the Dukosi C-SynQ® communication protocol. The protocol is designed to ensure synchronous measurements, with immediate and robust communication, which is particularly advantageous in an EV environment where the vehicle can undergo sudden acceleration.

For other applications, the DK8202 System Hub can also be installed into a scanning tool with near field antenna that can directly read each Cell Monitor's information in many scenarios such as cell manufacture, shipping, battery repair, or second-use evaluation. The System Hub electronically interfaces to a standard microcontroller interface for which Dukosi provides an API (application programming interface) that runs on the scanning device microcontroller.

Dukosi's solution works for all cell formats, including prismatic, pouch, and cylindrical cells, and can support a wide range of cell chemistries and pack architectures. The Dukosi Applications Engineering Team assists customers in integration solutions specific to their cell, module, and pack designs.

Dukosi's contactless battery architecture advantages

Dukosi chip-on-cell technology significantly reduces wiring and connectors in a battery pack, as shown in the diagrams below. This novel battery architecture provides cost advantages throughout the production stages, such as streamlined assembly, testing, and reduction in manufacturing equipment and manual labor.



Representative diagrams showing the simplicity of the Dukosi chip-on-cell architecture (left) versus a typically complex wired BMS design (right)

By reducing the number of parts used, the energy required to make it, and the greater potential for reuse in a circular economy, manufacturers also reduce the carbon footprint of the battery, which contributes to meeting corporate environmental goals and regulatory requirements.

Cell modules connected to an AFE within a wired BMS[3]	Dukosi Cell Monitoring System
Shared measurement of cell voltages within the module via sensing harness	DK8102 Cell Monitors measure each cell directly
Sequential voltage measurement (shared/multiplexed ADC)	Synchronized voltage measurement (one ADC per cell)
One temperature sensor per several cells	Direct temperature measurement of every cell
No data storage for provenance data, SoH history/other	On-cell static history, lifetime data logging, usage information, and other compliance data can be stored
Measurement while vehicle is running or battery is charging	Continuous measurement and usage history, 24/7 monitoring
No measurement system if BMS is separated from modules or cells	Modules and individual cells continue to produce data outside of the battery pack

On-cell lifetime traceability benefits beyond State of Health

The ability to access 24/7 usage history, even when the battery pack is in shipping and storage, can be extremely valuable. Should a warranty claim be made for a failed battery pack, the battery manufacturer can determine if the battery pack experienced temperatures outside its safe range or was charged or discharged improperly. Conversely, if a cell failed and all parameters were correct for storage and usage, this could help determine that the cell failure was not from misuse. Such data can efficiently point warranty charges or insurance claims in the correct direction.

The chip also offers additional data storage capacity to help manufacturers meet other regulatory requirements, such as the sharing of critical mineral provenance data. This data can be accessed via links where users can learn the sources of the minerals and access validation certificates from third-party assessment organizations such as IRMA[4] (Initiative for Responsible Mining Assurance).

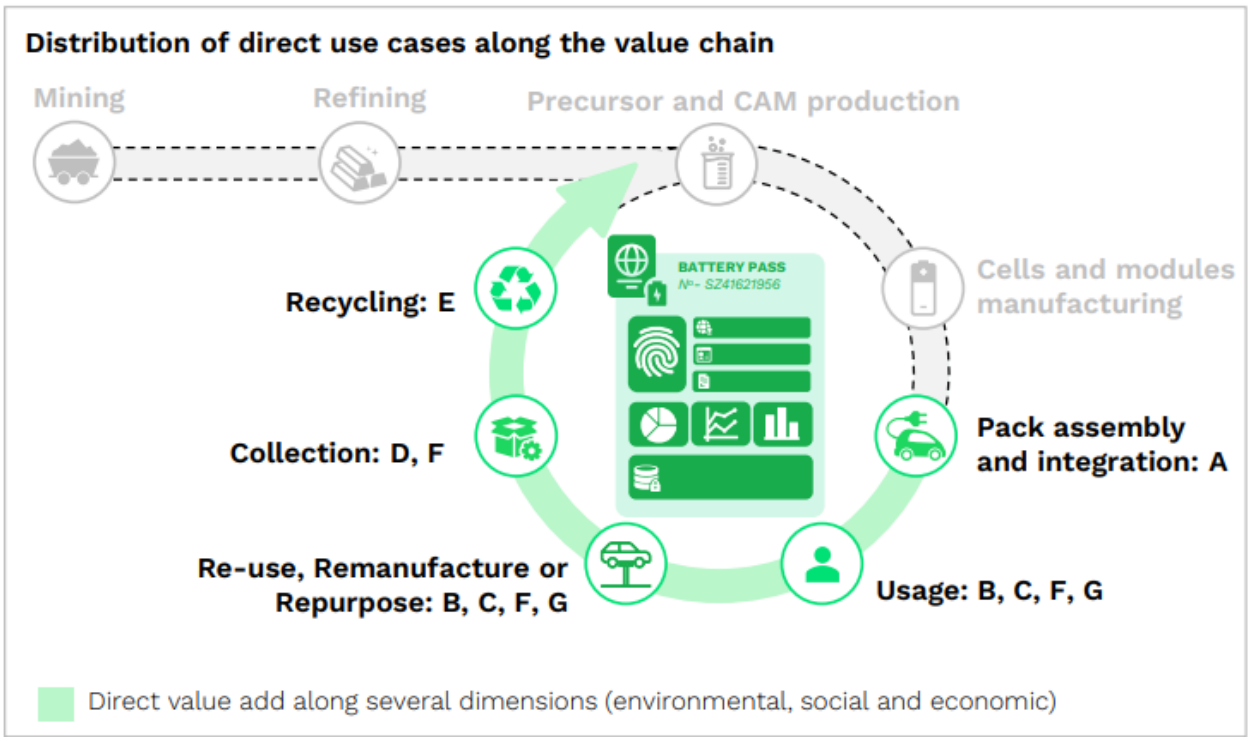
[3] Analog Front End - Measures voltage of multiple cells in series (usually 6, 8, 12, 18 or 24 cells)

[4] IRMA (n.d.). *Assessment*. Initiative For Responsible Mining Assurance. Retrieved October 9, 2023, from https://responsiblemining.net/what-we-do/assessment/

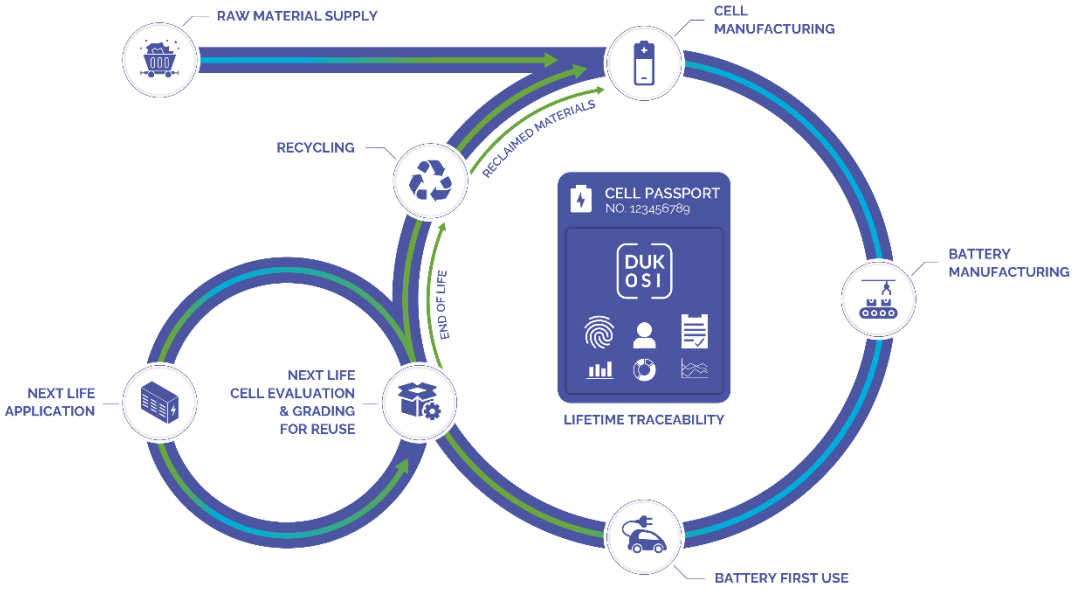
Creating a path to a sustainable circular economy

Ability to determine the SoH on a cell-by-cell basis rather than on a whole-battery or modular basis is far more advantageous, as it is possible that the majority or a larger number of cells in a battery are still completely safe and can be reused in a second battery pack.

Dukosi's cell monitoring solution also provides the path to creating a battery circular economy, as assessed in the Battery Passport Value Assessment by the Battery Pass Consortium. When a cell manufacturer adopts Dukosi's chip-on-cell solution early in the cell lifecycle, Dukosi enables a more complete circular economy thanks to its Cell Passport providing lifetime traceability data that can be analyzed at any time from manufacturing to recycling.



EU Battery Pass direct benefits to the circular economy highlighted by the Battery Passport Value Assessment by the Battery Pass Consortium



Battery circular economy when using the Dukosi cell monitoring solution

Second-life uses and the value of the circular economy

Auto manufacturers are motivated by buoyancy of the second-hand battery market; when second-hand cell values rise, the cost of building an electric vehicle goes down because the demand on just manufactured cells decreases. While vehicles need grade-A batteries, some applications such as stationary battery energy storage applications can use lower grade cells, such as reusing those already used once in EVs. It is estimated that 100M EV batteries are expected to reach retirement by 2032[5], so there is a significant need to address this with an effective solution that enables next-life use.

The Battery Passport Value Assessment[6] by the Battery Pass Consortium notes that SoH ("performance data") could simplify the residual value determination and reduce procurement, including technical testing costs for independent operators, by ~ 2-10%, while composition and dismantling information within the Battery Passport could make the recycling process more efficient and reduce the costs for pre-processing and subsequent treatment in recycling by ~ 10-20%.

By providing accurate cell-level data, Dukosi chip-on-cell technology can achieve not just these aforementioned advantages, but goes even further, streamlining cell grading efforts even after

[5] Battery recycling takes the driver's seat – McKinsey & Co.
[6] Battery Passport Value Assessment: https://thebatterypass.eu/assets/images/value-assessment/pdf/2024_BatteryPassport_Value_Assessment.pdf

battery dismantling through the availability of on-cell storage that provides lifetime traceability with a unique ID, materials provenance and 24/7 data and event logging.

In addition, the Battery Passport Value Assessment also recommends "additional data attributes should be allowed in a separate “beyond regulation” battery passport section to enable the battery passport being used as a B2B tool”, which is precisely where Dukosi technologies apply.

Will there be a global Battery Passport?

At the time of this publication, the answer is unclear. On one hand, it seems unlikely as countries regulate and govern very differently. However, the drivers toward a sustainable battery value chain are different this time. It’s not ‘just’ about the environment or ‘just’ about corporate social responsibility; every government is motivated to retain control of their battery-critical minerals, which means not exporting end-of-life vehicles or scrap batteries to other countries as an inexpensive way to get rid of them.

Dukosi chip-on-cell technology can provide easier access to cell-level data that can enable more accurate SoH calculations, while also streamlining compliance with global Battery Passport regulations, and even exceeding them. Dukosi is committed to working with various stakeholder groups to pilot battery passport solutions, develop standards, and much more.

Distribution

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