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Benefits and Pitfalls of Better Lifetime Data – The Case of Batteries in Mobile Electronic Equipment

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Abstract: Batteries are continuously gaining prominence in an ever-increasingly connected and mobile world. Battery lifetime is a topic of extensive research and discussions. Smart batteries are able to quantify, track, and report their own health status during their use phase, however, the availability of such data to consumers, repair, reuse, and recycling actors is often restricted. This paper establishes how batteries in mobile electronic devices track and report their own health status and to which extent this feature is implemented in today's smartphone and notebook batteries. The paper further illustrates potential benefits and drawbacks of full battery health data transparency with respect to the lifetime of products and the Circular Economy at large.

Introduction

Premature obsolescence of products, including electric and electronics equipment (EEE), has been a topic of much debate in recent years, amplified by the political and societal ambition to transition the EU to a Circular Economy, in which products last longer and the generation of waste is minimized. The reliability of products, including the identification of common failure modes and mechanisms, is usually evaluated extensively before products are released to the market, using accelerated stress tests and lifetime models. However, the environmental conditions and use patterns during real use of products in the field can only be approximated with such methods. In most cases, once a product is in the hands of users, little information is available about the actual degradation processes until a failure occurs. The actual failure mode and mechanism that have occurred, may or may not be identifiable in an ex post analysis.

Batteries in electronic devices have a special status in this context. On the one hand, they are considered "consumables", even in case of rechargeable batteries, as they are expected to degrade quicker than the overall product under normal use conditions. On the other hand, batteries are, in principle, able to track details of their own state of health and ageing progress, something that few other product component can actively do.

In the following sections, this paper aims to shine a light on the technical prerequisites of battery state of health tracking, the extent to which manufacturers make use of it, and the potential benefits and drawbacks such insights bring to consumers, repair actors, the second-hand market, and the recycling sector.

Battery lifetime data tracking

Smart batteries make use of battery management systems (BMS) composed of dedicated integrated circuits (IC) to track and report lifetime data in addition to carrying out safety and performance-related tasks such as monitoring battery voltage, current, and temperature. For instance, fuel gauge ICs estimate a battery's state of charge (SOC) in order to inform the user on the remaining use time until the next charge is required. Estimations make use of a variety of approaches involving look-up tables, ampere-hour integral, model-based estimation, or data-driven estimation methods (Xiong et al. 2018). The state of health (SOH), defined as the capacity the battery can store at a given time expressed in percentage of the battery's design capacity, is estimated via measurements of cell impedance or resistance, coulomb counting, or compute-intensive adaptive battery models (Berecibar et al. 2016). The SOH informs users on the irreversible capacity fade that progresses over time and with use. Smart batteries may also count the number of charge-

discharge cycles, defined as an amount of discharge approximately equal to the battery's design capacity (SBS IF 1998).
These data points may serve as simple indicators of a battery's health status and may enable fact-based decision-making regarding replacing a battery with faded capacity or continued use of a healthy battery in a second-hand or re-use scenario. For instance, if a smartphone battery is only one year old, has been subjected to 200 charging cycles and reports a SOH of 94 %, it can be assumed to be in perfect working order and is qualified for a continued use.

Implementation of lifetime data tracking in mobile ICT devices

Due to space constraints, printed circuit boards (PCB) embedded in smartphone batteries tend to be minimalistic. Figure 1 shows a PCB from an Android smartphone single-cell battery. The PCB is populated with one electronic package, housing a combined protection IC and dual channel MOSFET, in addition to a current sense resistor, the battery interface and a small number of passive components. The protection IC provides detection of overcharge, overdischarge, and charging and discharge overcurrent. The FETs are used for switching on an off negative and positive output terminals (ITM Semiconductor 2012).
Additional BMS components may be embedded into the smartphone electronics rather than into the battery. However, a survey of available online information suggested that Android smartphones do not track additional lifetime data. As such, no data on the SOH, cycle count or battery age exist to inform relevant actors on the condition of a used device battery. This gap is partially filled by third-party apps that estimate SOH via access to basic battery data such as current, the SOC and the nominal capacity (Figure 2). However, due to the absence of sepcialized hardware, these apps have no information on cycle count and battery age either, and they require multiple charge-discharge cycles to produce accurate SOH estimates, making the process time-consuming and therefore not ideal for quick decision-making.

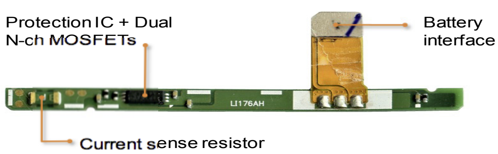

Figure 1. Battery management PCB extracted from an Android smartphone battery.

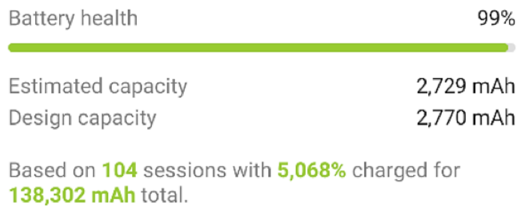

Figure 2. Screenshots of the Android application AccuBattery displaying the estimated design capacity, full charge capacity and SOH.

In contrast, batteries in iOS-operated smartphones commonly have more complex BMS hardware embedded into the battery PCB. In addition to protection ICs and MOSFETs, this typically includes a fuel gauge IC that tracks and reports the cycle count, SOH, and manufacturing date, among others (Texas Instruments 2018). iOS devices hence are able to track and report their health status to the user and other interested parties. The cycle count, design capacity and cell temperature are not immediately accessible in iOS but can be displayed via third-party apps (Figure 4).

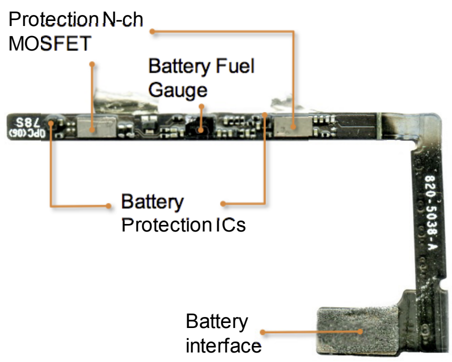

Figure 3. Battery management PCB extracted from an iOS smartphone battery.

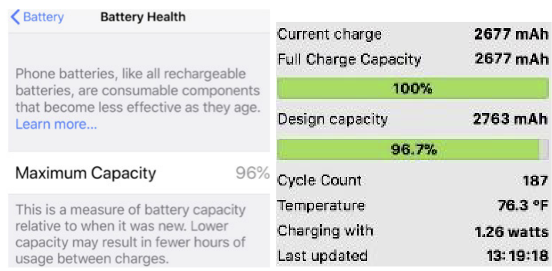

Figure 4. Screenshots of the battery health settings within the iOS settings displaying the SOH (left) and the coconutBattery application displaying additional data incl. the cycle count (right).

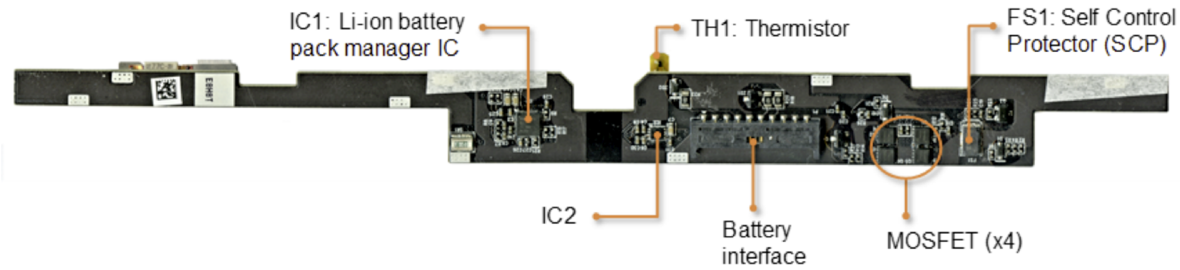

Figure 5. Battery management PCB and its components extracted from a business notebook battery.

Space constraints also apply to notebook battery PCBs, but to a comparatively lesser degree. Current notebook battery packs commonly consist of three, four or more cells and include a larger PCB with additional components and functionality. Figure 5 shows the example of a PCB extracted from a current-generation business notebook. IC1 controls and regulates charging, cell balancing, and determines the SOC, SOH, and cycle count, among other functions. The thermistor senses the temperature in one of the cells. The battery interface connects the battery pack to a host device, and fuse (FS1) and MOSFETS are responsible for preventing overvoltage, undervoltage, overcurrent and overtemperature. The exact function of IC2 could not be identified. With this hardware setup, notebooks batteries commonly track the relevant health data, including SOH and cycle count. However, previous studies found that not all relevant data are always accessible to the user (Clemm et al. 2016).
It can be concluded that, in principle, both smartphone and notebook batteries are technically able to track and report on their health status. However, it depends on the device manufacturer (OEM) to invest into the additional hardware and software to enable such features, and it is also up to the OEM which actors are granted insight into the data.

Benefits and potential pitfalls of better availability lifetime data

As has been pointed out in the previous sections, users of mobile ICT devices currently only have limited access to the lifetime data of their device batteries. Several studies have recommended that full access to basic battery health data should be given to relevant actors (e.g. Tecchio et al. 2018, Clemm et al. 2016).
The following subsections illustrate potential benefits and pitfalls of better availability of lifetime data for users, second-use and repair actors, and the recycling sector. All considerations are based solely on the authors' deliberations and no in-depth impact assessments were carried out to quantify potential benefits and drawbacks to date.

Users

Keeping mobile electronic products in use longer is considered a significant lever to decrease their overall environmental impact (Proske et al. 2016), and the durability of the battery may have a direct impact on the use phase of the product it powers. If the battery's health status was to be fully accessible, it is conceivable that users adapt their behavior accordingly, for instance by adapting battery-saving charging habits. Furthermore, in cases where device batteries degrade quicker than expected, users' warranty claims may be underpinned with factual data.
Table 1 illustrates potential benefits and drawbacks of full transparency on battery health data for consumers.

Full access to battery health data for users
Potential benefits
▪ Incentive for users to adopt behavior that slows down battery degradation ▪ Consumer empowerment with regard to in-warranty battery failures ▪ Users may benefit from a "race to the top" as manufacturers are incentivized to optimize battery durability
Potential pitfalls
▪ Observable degradation of battery may elicit "psychological obsolescence" (e.g. "My device is not perfect anymore, I want to replace it") ▪ Incentive to deliberately provoke battery ageing before expiry of warranty period in order to be eligible for in-warranty battery replacement

Table 1. Potential benefits and drawbacks of battery lifetime data availability for consumers.

Repair actors and second-hand market

After the first use phase in a mobile device, batteries may still retain a substantial share of their initial capacity and may be qualified for a second life in the same application or as a spare part, rather than being disposed of. Table 2 lists potential benefits and drawbacks of full battery-health data transparency for this sector.

Full access to battery health data for repair actors and the second-hand market
Potential benefits
▪ Continued use of batteries that may otherwise be disposed of due to unknown health status ▪ Increased trust in used devices by potential buyers due to known battery health status
Potential pitfalls
▪ Conservative SOH-based decision-making may lead to premature disposal of used batteries ▪ Second-hand market buyers may not be willing to buy devices with battery health below a certain threshold

Table 2. Potential benefits and drawbacks of battery lifetime data availability for repair actors and the second hand market.

Remanufacturers and repair shops are in need of battery health data to be able to choose an alternative to disposal of used batteries. Making an informed decision based on technical facts may help keep the battery or the device itself in use for as long as possible, thereby saving precious resources. Data availability may enable quick decision making in regard to continued use or disposal of a used battery.

The potential effects of full battery health data transparency on the second hand market are considered ambivalent. While transparency may lead to increased trust towards used devices, it may also lead to devices with lower battery health, which are in otherwise great condition, not being accepted in second hand markets. Figure 7 shows the example of a second-hand market battery offer on a popular German-language second hand platform, stating the SOH of a spare iOS smartphone battery.

Figure 7. Screenshot of an offer for a used iPhone battery on a second-hand market place, stating the remaining capacity and SOH (ebay 2019).

Recycling sector

The EU economy is reliant on the import of many strategic metals, some of which are considered critical raw materials (CRM). Securing access to these materials is crucial in order to stay competitive and avoid shortages in the future. Batteries contain CRM, and their market penetration is ever-increasing. More than 26,000, tons of batteries placed on the European market in 2018 were batteries in electronic devices, with an increasing trend (RMIS 2019). In an effort to close the loops of precious materials from batteries, reliable data on the timeline when batteries reach their end-of life is crucial. However, such data is hardly available. More precise estimations on the time spent in stock, meaning the time between battery sale and waste collection, is needed to improve the knowledge base on urban mine stock and flow models. For instance, the Urban Mine Platform (UMP 2019) was developed under the EU-

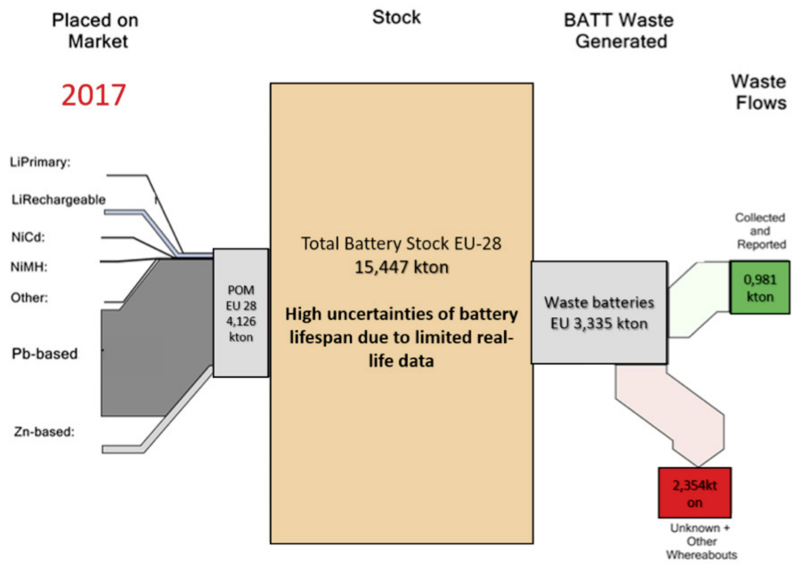

Figure 6. Stock and flow model of batteries in Europe for 2017 (adapted from Huisman et al., 2017).

funded ProSUM project and provides a state-of the art data platform, where an extensive amount of data from multiple sources was combined to comprehensively estimate the stocks and flows of batteries and their material content in the European market (Figure 6). However, the method used to estimate the duration of batteries' use phases could very well lead to underestimations of the total battery lifetime, by not taking into account second-use scenarios. The absence of reliable real-life data was identified as one of the weak points in the modelling. Having real data from the field would improve the stock and flow model and lower the uncertainty level and thereby give more reliable predictions of return flows on material level. This information is valuable for recycling companies to make strategic decisions on e.g. future investments. Furthermore, improved data could provide a better indication of the flows which are labelled as "unknown whereabouts" in the model (Figure 6). No data is available for these battery flows making up over 70 % of the estimated waste streams, leaving a large amount of valuable CRM flows untracked.
No pitfalls have been identified for the availability of such data to the recycling sector. However, questions remain on the practicability and accessibility of the data from the manifold battery-driven electronic equipment in facilities along the e-waste recycling value chain. At the very least, the potentially available information base for the age and condition of smart batteries could be increased. For instance, data could be retrieved from device batteries via sampling of functional devices.

Device manufacturers
Last but not least, several potential benefits and drawbacks were identified for the hypothetical case of full battery health data transparency from the manufacturer's point of view (Table 3).

Full access to battery health data for OEMs
Potential benefits
▪ Knowledge on battery behavior and battery-related user behavior in the field may allow for optimizations ▪ Potential to stand out from the competition with comparatively higher battery durability
Potential pitfalls
▪ Increased cost for data tracking ICs in BMS ▪ Increase of in-warranty battery failure claims ▪ Lower battery durability compared to the competition may look unfavorable ▪ Efforts required for standardization of metrics to create a level playing field for SOH estimation

Table 3. Potential benefits and drawbacks of battery lifetime data availability for OEMs.

Conclusions and recommendations
While the ability of batteries to track and report their own state of health is a unique feature, the effects of full transparency of such data in a Circular Economy are not unambiguous. Much depends on the users' behavior, resulting in the need for sociological studies to underpin assumptions on benefits and drawbacks. In addition, impact assessments should be carried out to quantify the effects on product lifetime and consequently resource consumption. Before considering tracking and reporting of battery lifetime data as a requirement under product policy instruments such as ecolabels or the Ecodesign Directive, additional costs for manufacturers should also be quantified. Additionally, standardization efforts on the estimation of SOH and other relevant parameters is encouraged to warrant a level playing field when comparing the durability of batteries from different manufacturers and in different applications.

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