Sustainability of Power Electronics and Batteries: A Circular Economy Approach

by Ariya Sangwongwanich, Daniel-Ioan Stroe, Chris Mi, and Frede Blaabjerg

Power electronics and battery energy storage are the key enabling technologies for high-efficiency energy conversions to realize green transition. With an increasing demand for electrification, renewable energy integration, and energy saving, more and more power electronics and batteries are being utilized. Consequently, their impact on the environment becomes of great concern, as they are responsible for a considerable amount of material usage including critical raw material during production and

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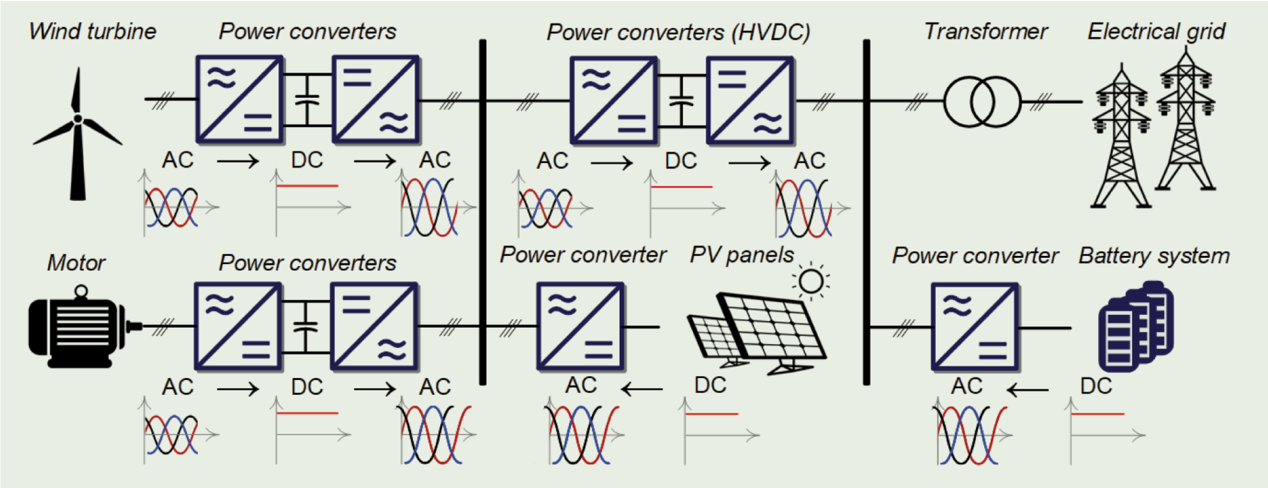

FIG 1 Examples of power electronics and battery energy storage in energy conversion system with various applications (e.g., wind turbine, motor drive, and photovoltaic systems).

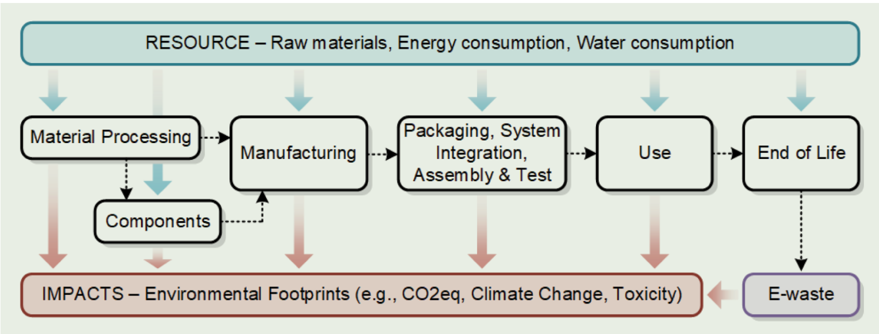

FIG 2 Traditional linear economy based on "take-make-waste" life cycle for power electronic and battery components and systems (adapted from [10]).

e-waste generation after the end-of-life. Going forward, the development of power electronics and batteries needs to change from the traditional linear economy "take-make-waste" to a circular economy, where the concept of reuse, remanufacturing, and recycling needs to be considered as part of the product life cycle. In this article, challenges and potential solutions to enhance the sustainability of power electronics and batteries through the concept of circular economy will be addressed both from the design and end-of-life management perspectives. Existing design tools and their application in the power electronic industry will also be discussed as well as future demand.

Introduction

Power electronics (PE) and battery energy storage systems (BESS) are the key enabling technologies for high-efficiency energy conversions to realize green transition and decarbonization, as illustrated in Figure 1. With an increasing demand for electrification, renewable energy integration, and energy-saving, more and more power electronics and batteries are being utilized. According to [1], 14% of all new cars sold worldwide were electric in 2022, and it is expected to reach 30% by 2026 [2]. It is estimated that the installation of power electronics and batteries will reach 100 TW and 15 TWh per year in 2050 in order to achieve the net-zero emissions target [3]. In that scenario, the environmental impact of such systems becomes of great concern, as they are responsible for a considerable amount of material usage including critical raw material and resource consumption during manufacturing. Moreover, with the traditional linear economy "take-make-waste," the majority of power electronics and batteries will contribute to a significant amount of e-waste when they reach their end-of-life. It is projected that by 2050 the amount of e-waste generated per year could reach 120 million tons with the current reuse and recycling rates [4], which are relatively low (e.g., less than 20% of e-waste is currently being collected and recycled [5], [6], [7]).

Accordingly, a paradigm shift in the design and development of power electronics and batteries is needed, where the circular economy approach needs to be applied. The concept of reuse, remanufacturing, and recycling needs to be considered as part of the product life cycle [8], [9], [10]. We need to be better at the design, utilization, and end-of-life handling of such systems to minimize their environmental impact. However, there are both technological and societal (e.g., user perception and acceptance) barriers to realizing these concepts. In this article, the focus will be on the technical challenges and potential solutions.

Circular Economy

Traditional industry including electrical products is based on linear economy shown in Figure 2. The raw material is extracted to produce components, which later on are integrated into a product. Apart from the material usage, energy and other resources (e.g., water) are also consumed during manufacturing, being part of the product's environmental footprint. When the product reaches its end-of-life (or usually rather end-of-service), it becomes e-waste and in most cases ends up in landfills and incinerators. Power electronics and battery industries with the linear economy will face the following challenges as they are scaling up in the future [11]:

Circular economy is a concept to solve the above challenges by decoupling the economic growth from resource consumption through closing the loop.

- Lack of material, especially critical raw materials
- Risk of supply-chain interruption due to geopolitical conflicts
- Environmental footprint during manufacturing is magnified, especially for power semiconductor devices
- Growing amounts of e-waste and their impact on environmental and human health

It can be seen that power electronics and batteries may become part of the problem for the environment rather than the promising solution with the current linear life cycle.

Circular economy is a concept to solve the above challenges by decoupling the economic growth from resource consumption through closing the loop, as it is illustrated in Figure 3 [10]. Different "R-strategies" can be applied to "keep the component/material in the loop," e.g., reuse/refurbish for new applications, remanufacturing into new components/products, and recycling components back into raw material. It is important to consider the value kept in the component/products during the entire process, where the value generally decreases when moving from the inner loops (e.g., reuse and remanufacturing) to the outer loops (e.g., recycling). For instance, reuse and remanufacturing should be prioritized over recycling as they keep the function of the component and therefore its value. Besides, the required resource and the environmental footprint also generally increase as the R-strategy moves toward the outer loops. However, there are also challenges for the remanufacturing strategy such as the requalification of (electronic) components to be reused and the diversity of the products returned from the field. These issues have a strong impact on the product performance and reliability.

To efficiently "close the loop" in practice, the product has to be designed having those life cycles in mind—known as the Design for X (DfX) principle. For instance, remanufacturing requires the components to be reused in the new product. This means that disassembly is part of the product life cycle and should be considered during the hardware design (and integration). Similarly, increasing modularity is also a common strategy to improve the product's capability for repair and remanufacturing, which can be applied through, e.g., using common building blocks. Recycling efficiency and yield are on the other hand strongly dependent on the material characteristics. Certain material compositions or permanent connections can be very difficult to sort and separate during the recycling process and thus reduce the recycling yield and/or demand additional pre-treatments. Therefore, the choice of material combination used in the product will also determine its ability to be recycled. While it is beyond the scope of this article, supply-chain also plays a crucial role in enabling a take-back system through reverse logistics and the manufacturing process also needs to be able to handle higher tolerance of the raw material and component characteristics in comparison to the virgin material or new components.

Power Electronics

The concept of circular economy can be applied to power electronics at different stages of the life cycle. In this section, challenges and potential solutions that can be applied during the design phase, use phase, and end-of-life phase will be discussed.

Design Phase

It is crucial to apply the circular economy approach as early as possible during the design phase of power electronics

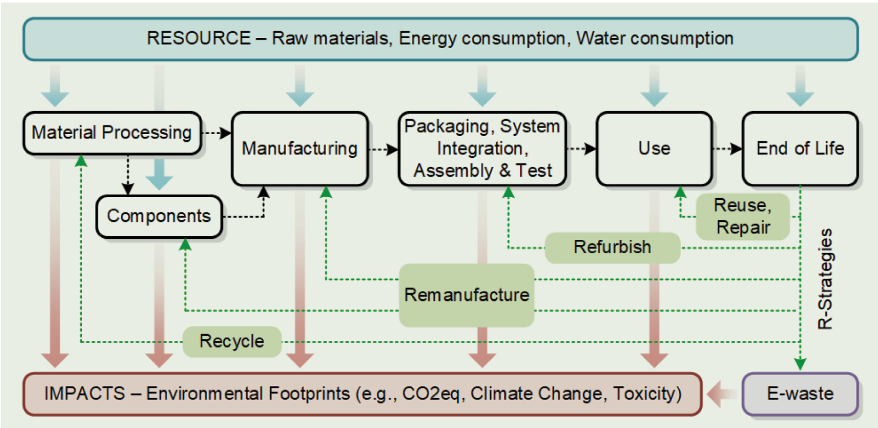

FIG 3 Circular economy based on R-strategies life cycle for power electronic and battery components and systems (adapted from [10]).

(even at the conceptual phase), as 80% of the sustainability impact is already defined during the design phase [3]. The design of power electronics is generally an optimization problem, where the designer aims to fulfill the design targets through a proper selection of circuit topology, components, and integration techniques. Here, environmental impact can be added as another design dimension in addition to the typical performance-related design targets, e.g., efficiency, power density, reliability, and cost. The design framework for performance-circularity optimization of power electronics is illustrated in Figure 4, where the metrics related to sustainability, e.g., resource consumption and environmental impact, are included as part of the design targets.

The design of power electronics is generally an optimization problem, where the designer aims to fulfill the design targets through a proper selection of circuit topology, components, and integration techniques.

Life-cycle assessment (LCA) is a possible solution to quantify the environmental impact over the entire life cycle of different design solutions [12], [13], which can help the designer to make a qualified decision of the design choice. It analyzes the product's impact on resource usage (e.g., material and energy consumption) and the environmental footprint, e.g., CO_2eq emission and toxication, considering the material in the components and the process involved in all life cycle stages, e.g., raw material extraction, manufacturing, and end-of-life stages. However, the availability and verification of data used in LCA (e.g., life cycle inventory) can be challenging, as there are currently no standard databases for LCA, especially for power electronic applications. Using data from different sources can introduce large variations of the environmental footprint, resulting in high uncertainty in the analysis or biased comparison. Upcoming EU regulations are pointing toward the direction where digital product passport (DPP) will be mandatory for electrical and electronic products including power electronics (and batteries) [14]. It is expected that material data and sustainability data (e.g., environmental footprint) will be included as part of the DPP, which highlights the importance of the product's environmental footprint as part of compliance.

Design trade-off will need to be addressed when the aspect of the environmental footprint is included in the multi-objective design optimization [3]. In most cases, the traditional design target of increasing power density will still benefit the environmental footprint through reducing the material usage and waste generation of the product. This can be practically achieved by increasing

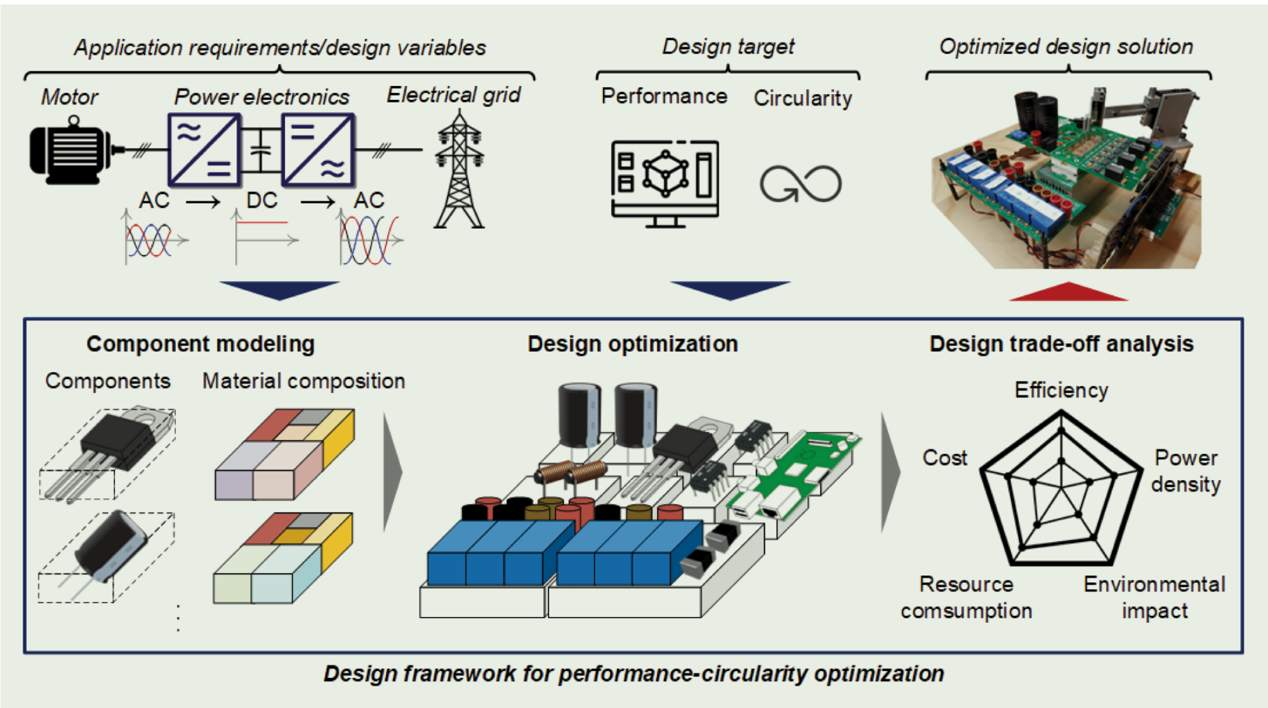

FIG 4 Design framework for sustainable power electronic systems where the performance and circularity are considered during the design optimization and impact evaluation to enable circular economy.

the integration level of the circuit design to reduce cables or improving efficiency to reduce the size of the heatsink. However, increasing the integration level may on the other hand limit the capability of the product to be disassembled and therefore remanufactured. The compromise between different design aspects (and different loops in Figure 3) needs to be carefully evaluated considering the entire life cycle of the power converter, as shown in Figure 4.

Minimizing energy loss can significantly reduce the environmental footprint from the energy source, which is particularly important for a power converter used in an energy network with a relatively high share of fossil fuel-based generation.

Use Phase

During the use phase, high-efficiency and long-lifetime design generally contribute positively to the environmental footprint of the power converter. Minimizing energy loss can significantly reduce the environmental footprint from the energy source, which is particularly important for a power converter used in an energy network with a relatively high share of fossil fuel-based generation. An example presented in [12] demonstrates that the energy loss from the stand-by operation during the night of the photovoltaic inverter can account for close to 50% of the overall product's CO_2 emission for the electrical grid with the conventional energy mix. Thus, the efficiency during light-load or stand-by operation cannot be neglected.

The influence of efficiency needs to consider the entire operating life span of the power converter. High-efficiency design solutions may utilize more advanced (e.g., wide-bandgap power devices) and/or a higher number of components (e.g., multi-level converter topology), which could result in a high initial environmental footprint during manufacturing. However, the initial offset will be compensated during the use phase through the energy saving over the life span, as shown in Figure 5, and therefore highlights the importance of long-lifetime design, where reliability is an important aspect to avoid failure during the use phase. Besides, keeping the product in the system through lifetime extension is also an effective solution to reduce waste generation. However, this does not necessarily mean that all components must be designed to survive long-lifetime operation, as it can be challenging both technically and economically for certain components. It can be expected that components that are prone to aging such as power devices and electrolytic capacitors will need to be replaced as part of predictive maintenance. Therefore, assessing the remaining useful life of components through condition monitoring is crucial to avoid failure during the use phase. If allowed by the application requirements, adapting the operating condition to reduce the stress of the components is another possibility to extend the component's lifetime [15]. Moreover, the ability to access and replace the components is also important and needs to be considered during the hardware integration design.

End-of-Life Phase

After the use phase, the product, e.g., a power converter, is considered to reach its end-of-service/life. However, this is not necessarily the same as the components' end-of-life. Several components in the power converter (e.g., magnetics and mechanical parts) may still be capable of another life cycle either with the same application or another application with reduced loading stress condition. The main goal during the end-of-life phase is to assess the condition/remaining value of the components and then find the most suitable path (i.e., R-strategies) for the product/components to close the loop following the diagram in Figure 3. It is also worth mentioning that for the same R-strategy, e.g., remanufacturing, there might be several possible applications with different performance and reliability demands for the components. Thus, understanding the component's remaining value/capability and matching it with the (new) application requirements are the key elements. There are several aspects to be considered when choosing the R-strategy for the component/system. From the technical perspective, the component has to at least fulfill the minimum performance requirements (e.g., electrical, thermal, and mechanical performance) of the applied R-strategy and the reliability target of the

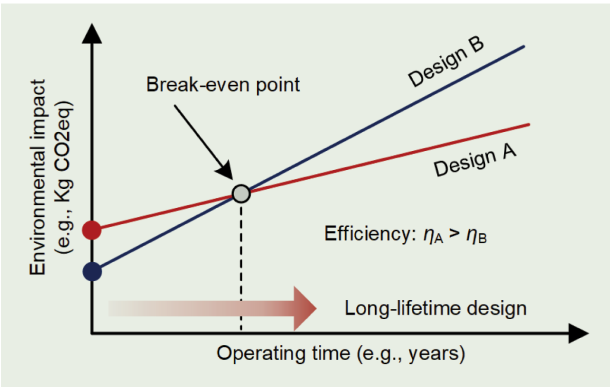

FIG 5 Environmental footprint over the lifespan of different power electronic designs: design A prioritizes the efficiency while design B prioritizes the initial environmental foorprint during manufacturing (adapted from [3]).

application. In practice, it will be more attractive if the reused component can offer a competitive performance (and reliability) as the new component for the considered R-strategy and application. At the same time, the environmental impact also needs to be quantified and benchmarked for different R-strategies, which can be done by applying the LCA for each R-strategy scenario. Additionally, the economic feasibility of different R-strategies should also be evaluated. In the end, the selection of the R-strategy will be dependent on the trade-off between performance, environmental benefit, and economic feasibility.

In general, priority should be given to the inner loop (i.e., reuse > remanufacturing > recycling) for realizing an efficient circular economy. If direct reuse of the product is not feasible (e.g., due to aging), the components inside the power converter can either be remanufactured into a new product, recycled back into raw material, or discarded as e-waste. As the decision-making between different paths is strongly dependent on the remaining lifetime/value, a method for assessing and requalifying the components to be reused after the end-of-life will be crucial to enable remanufacturing while maintaining performance and reliability requirements. Currently, this is mostly done through visual and mechanical inspections at the product level with a focus on mechanical parts (e.g., enclosure and chassis) rather than electronic parts. However, it is expected that information from the DPP such as repair and maintenance history will also be utilized in the future as part of the screening process before disassembling the product. For the component level, new testing and analyzing methods are required, as typical reliability and qualification testing approaches (which today are applied to new components) may not be suitable for reused components due to their non-homogenous characteristics. An example of the non-homogenous degradation characteristic of capacitors during the endurance testing is shown in Figure 6, where the divergence in the capacitance parameter further increases through the aging process and thus will be significant for the reused components. Apart from testing, the information on the use profile during the life span of product/components (e.g., the actual mission profile) will also be valuable information for assessing the remaining useful life of components. To assess the condition of multiple components, a local condition monitoring technique may not be sufficient, and a system-level modeling approach based on digital twins can be an attractive solution to address this challenge. These assessment tools will need to be developed and demonstrated in order to efficiently enable circular economy for power electronic systems.

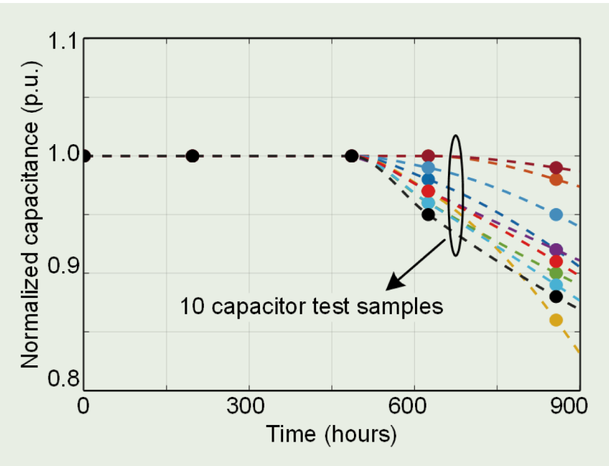

FIG 6 Degradation charateristic of capacitors under 900 hours endurance testing which represents typical degradation variation in power converters (from experimental endurance testing of capacitors).

Battery Energy Storage

The rapid development of the Lithium-ion (Li-ion) battery industry, led by the ever-increasing demands, has primarily focused on improving the batteries' performance (e.g., energy density, thermal stability) and lifetime. Nevertheless, sustainability and circularity aspects were heavily neglected, and EV batteries are not designed for recycling [16]. New regulations and incentives have been adopted worldwide to address this issue [17], [18]. It is expected that, in the future, most of the EV Li-ion batteries will follow the circular economy approach presented in Figure 7. A lot of emphasis is placed on reuse, repurposing, and recycling, which will be discussed in this section. To overcome some of these challenges, the possible use of batteries in second life applications should be addressed as early as the design and development phase of the EV battery system.

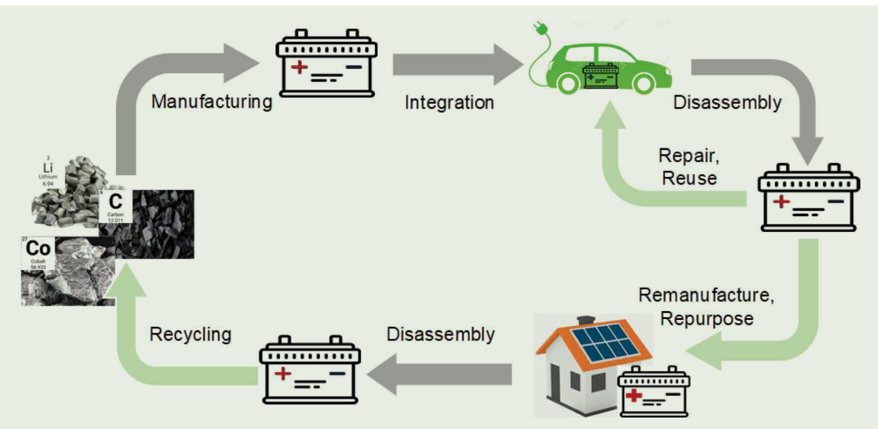

FIG 7 The life cycle of an EV Li-ion battery from the circular economy perspective.

Battery Recycling

Reaching circularity for Li-ion batteries is, however, a challenging task as all the aforementioned steps are in their infancy and were not industrially validated at a large scale. Li-ion battery recycling can be achieved by following three approaches: direct, pyrometallurgical, and hydrometallurgical methods [19], [20] as well as their combinations. Battery pretreatment is a mandatory step before applying any of these recycling methods [20]. Independent of the method, besides having a negative environmental impact, battery recycling is still a relatively inefficient and energy-demanding process, returning low economic benefits [19]. All these negative aspects hinder the widespread adoption and implementation of Li-ion battery recycling. Thus, to increase the economic benefits, more research and development are needed to improve the efficiency of Li-ion battery recycling methods, which at the same time should focus on all the battery components (e.g., not only on the battery cathode).

The most important aspect is the availability of effective state of health (SOH) estimation and diagnostics methods which are capable of estimating the available battery capacity as well as the degradation trajectory at the end of the batteries' first life.

Battery Repurposing

Re-purposing (i.e., reuse) Li-ion batteries into second-life applications (usually in stationary energy storage systems) represents another approach to address the circularity challenge (i.e., improved resource utilization). It is well known that when discarded from the EVs, the batteries are not "dead" but still have high levels of available capacity/energy, making them suitable for second-life applications, which are less demanding in terms of energy density and power capability. Nevertheless, several challenges need to be addressed before second life use of EV batteries becomes economically viable. The most important aspect is the availability of effective state of health (SOH) estimation and diagnostics methods which are capable of estimating the available battery capacity as well as the degradation trajectory at the end of the batteries' first life. This requalification is mandatory because mixing batteries with the same SOH value but different use histories (i.e., heterogenous batteries) will result in a short lifetime of the battery system in the second-life application and thus poor economics [21]. While battery SOH estimation algorithms have been extensively proposed in the literature, methods for reconstructing the battery's first life aging trajectory based on a limited number of points are still a bottleneck. Secondly, the batteries in the new generation of EVs are rather optimized for high energy density and power capability and not for a long lifetime, which makes them not ideal for a second life application because of their rapid degradation once they reach the end of the first life (i.e., approx. 20% capacity fade), as illustrated in Figure 8. On the contrary, batteries discarded from trucks and/or forklifts (see the battery degradation curve in Figure 9) might be a more suitable choice for second life applications. Thirdly, the operation requirements of a battery in second life application should be clearly investigated and defined, as harsh battery operations such as daily deep cycles (characteristic of residential PV-battery systems) and high C-rates (characteristic of ancillary grid services) might accelerate the battery degradation a shorten dramatically the battery life. Similar to power electronics, extending the lifetime through adjusting the operating condition is an attractive

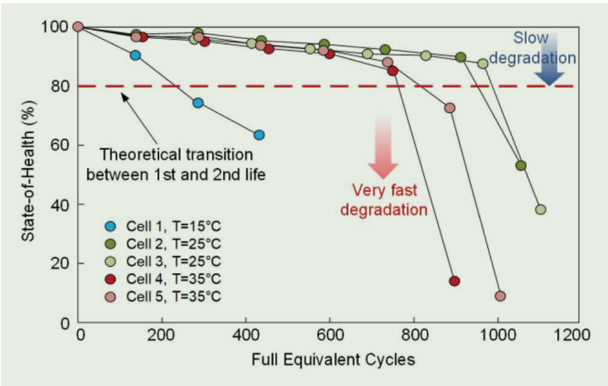

FIG 8 EV Li-ion battery SOH evolution showing very fast degradation at the hypothetical transition between 1st and 2nd life.

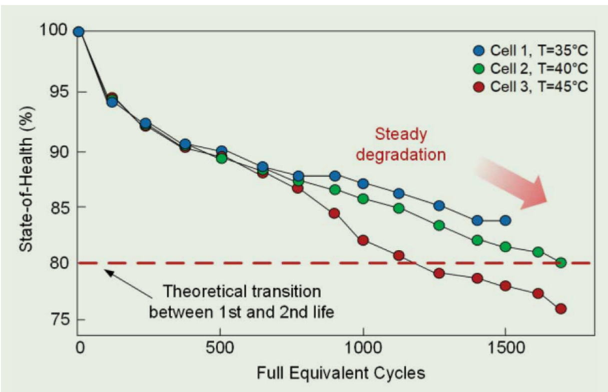

FIG 9 Forklift Li-ion battery SOH evolution showing no change in the degradation at the hypothetical transition between 1st and 2nd life.

solution for second life battery. Actually, battery operation in second-life applications with C-rates below 0.4 C (i.e., full battery charge or discharge in more than two hours) and DODs below 75% has proven excellent lifetime performance.

Conclusion

Increasing utilization of power electronics and batteries requires careful consideration of product sustainability to avoid negative environmental impacts due to resource consumption and e-waste generation. A paradigm shift in design and development is required where the concept of the circular economy should be applied during the design, use, and end-of-life management phases. While there are some differences between power electronic and battery life cycles, they do share certain similarities in the demands and potential solutions to enhance their sustainability. For the design phase, LCA is an essential tool to assess the environmental footprint and identify design trade-offs of different design solutions. During the use phase, efficiency and long lifetime are the two most important aspects to minimize the environmental footprint. At the end of life, the ability to assess the remaining value of components and select the most suitable R-strategies is an effective approach to keep the material/component in the loops. Innovations are also demanded especially in the area of requalification of reused components for remanufacturing. Non-homogenous characteristics of the reused components and batteries may require different ways of testing, characterization, and design to enable their full potential without compromising the performance and reliability of the product.

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