Closing the Loop on Circular Economy in Transportation Electrification: Reuse, Repurposing, and Recycling of Power Electronics and Electric Machines

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***Abstract*— The electrification of transportation is a pivotal step towards sustainable and environmentally conscious mobility. However, as the adoption of electric vehicles (EVs) and associated technologies continues to grow, the need for effective strategies to manage end-of-life components becomes increasingly crucial from both sustainability and economic standpoints. Obtaining essential rare-earth (RE) materials such as cobalt, lithium, neodymium, and terbium has become progressively more difficult and costly. Furthermore, the extraction and processing of these materials produce significant carbon emissions and the release of harmful toxins. The economic value of the materials and components in EVs are generally 20-30% higher than that in the conventional internal combustion engine (ICE)-based vehicles due to the increased use of lightweight and RE materials in batteries and electric motors. This paper aims to address the imperative of closing the loop on the circular economy within the realm of transportation electrification, with a specific focus on electric drives (i.e., power electronics and electric machines) as well as batteries with reuse, repurposing, and recycling technologies.**

Keywords*— *Carbon footprint, circular economy, end-of-life, environmental load unit, recycling, rare-earth materials, sustainability.

I. INTRODUCTION

The electrification of transportation is a pivotal step towards sustainable and environmentally conscious mobility. However, as the adoption of electric vehicles (EVs) and sustainable energy generation continues to grow, the need for effective strategies to manage end-of-life components becomes increasingly crucial. This paper addresses the imperative of closing the loop on the circular economy within the realm of transportation electrification, with a specific focus on power electronics, electric machines, and batteries, as shown in Fig. 1.

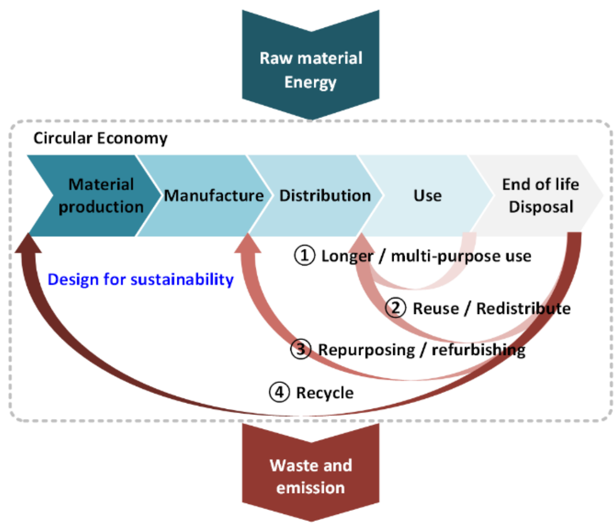


Fig. 1. Circular economy for electric vehicles, including design for sustainability.

The first pillar of closing the circular economy involves longer/multi-purpose use and reuse, emphasizing the refurbishment and redeployment of power electronics, electric machines, and batteries. By intensifying the use and extending the lifespan of these components through rigorous testing, refurbishment, and upgrade protocols, their utility can be maximized before considering recycling or disposal. Relevant technologies include integrated charger [1]-[8], multi-functional inverters for EV charging application [9], and EV battery swapping and refurbishing [10]-[12].

The second and equally crucial aspect is repurposing, where retired power electronics, batteries, and electric machines find new applications beyond their original design. This involves adapting and modifying these components for alternative uses, thereby extending their functional life, and contributing to a more sustainable and versatile electric ecosystem. To support these principles, this paper will delve into technological advancements and collaborative initiatives that facilitate the circular economy in transportation electrification. Case studies and ongoing research projects, including second-life EV batteries and electric machines in stationary [13]-[17] and mobile [18]-[21] applications will be introduced in detail.

The last pillar revolves around recycling practices tailored for power electronics, electric machines, and batteries. We

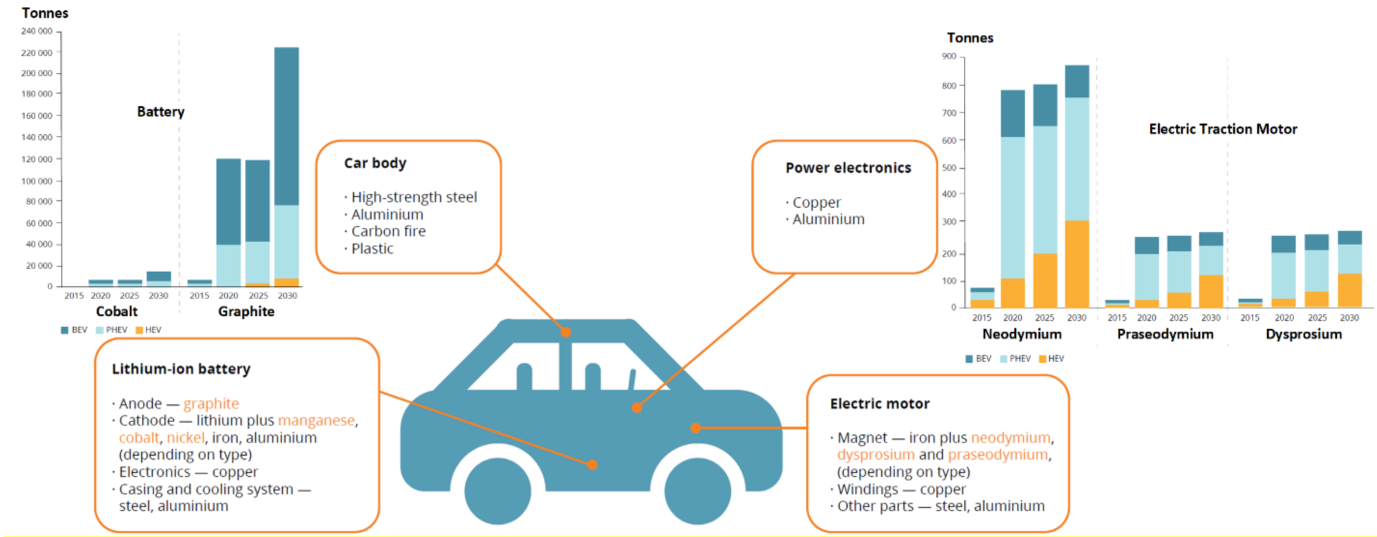


Fig. 2. Critical raw materials from electric vehicles and demand forecasts for 2030 [22].

explore innovative recycling methods that extract valuable materials from retired components, promoting a sustainable supply chain for critical elements like RE metals and reducing the overall ecological footprint of electric transportation systems. This paper will explore existing and state-of-the-art recycling technologies of batteries [22]-[23], electronic components (e.g., PCB) [24]-[31], and RE materials [32]-[37].

This paper advocates for a holistic approach to circular economy principles in transportation electrification, emphasizing reuse, repurposing, and recycling of electric drives and batteries. This paper will also discuss potential ways to strengthen the circular economy by introducing innovative design methodologies and material selections before manufacturing EVs, namely design for sustainability, as illustrated in Fig. 1 and 2.

This paper is organized as follow. Section II presents the concept of longer and multi-purpose use in electrified transportation to maximize power electronics and electric machine utilization factors. Section III investigates the reuse and repurposing of existing components such as EV batteries, methods to prolong their lifespan, and novel uses beyond their initial intent. Section VI will delve into recycling methodologies to extract valuable materials from existing components at the end of their lifecycle. Additionally, it will explore alternative electrical machine topologies based on design-for-reuse, which allows for the efficient recovery and reuse of PMs in new EVs. Finally, the conclusion summarizes the essential results.

II. LONGER AND MULTI-PURPOSE USE

The concept of longer and multi-purpose use in transportation proliferates due to the electrification where the vehicles are connected to the power grid through charging infrastructure becoming an integral part of an existing system as shown in Fig. 3. The unique nature of electrified systems gives an opportunity to intensify the use of the systems in multiple purposes alongside its main functionality. For instance, the average use of passenger vehicles is approximately one hour per day, which is less than 5%

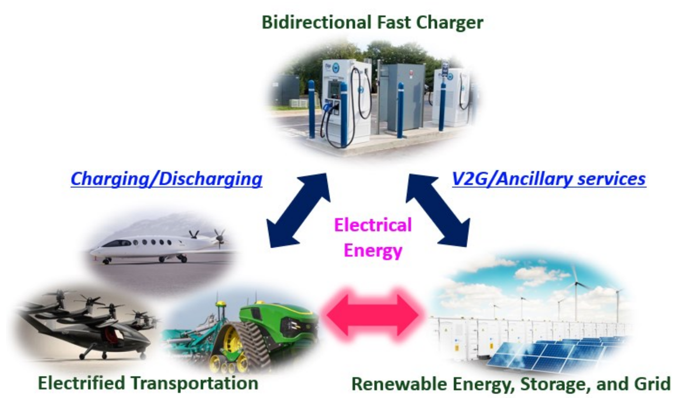


Fig. 3. Circular economy for electric vehicles including design for sustainability.

utilization factor [38]. From a sustainability perspective, it is critical to increase the utilization factor to its maximum as it means that energy and resources are being used more efficiently, leading to less waste.

There have been several innovations in electrified transportation where some of the key building blocks of the propulsion systems are functionally integrated and shared. Integration of on-board charger (OBC) with the propulsion system [1]-[9] is one way of maximizing the power electronics and electric machine utilization factors as shown in Fig. 4(a). It has also been reported that the battery swapping station (BSS) for EVs can be utilized as a stationary energy storage system (ESS) supporting power grid as shown in Fig. 4(b) [10]-[12].

III. REUSE AND REPURPOSING

Since the market introduction of lithium-ion batteries in the early 1990s, the demand for these innovative batteries with their high energy density and superior performance has been continuously increased as shown in Fig. 5. The transportation electrification has driven this trend and accounts for more than 60% of the total demand. The emerging consequences of the battery demand surge are the long-term availability of raw materials and the waste problems. It is critical to find

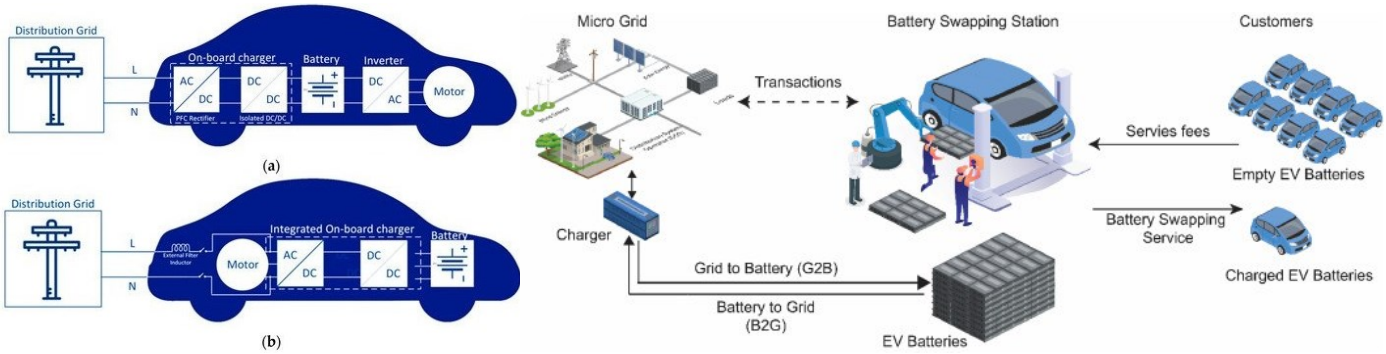


Fig. 4. Concept of integrated on-board charger [39] and (b) multi-purpose use of battery swapping stations [40].

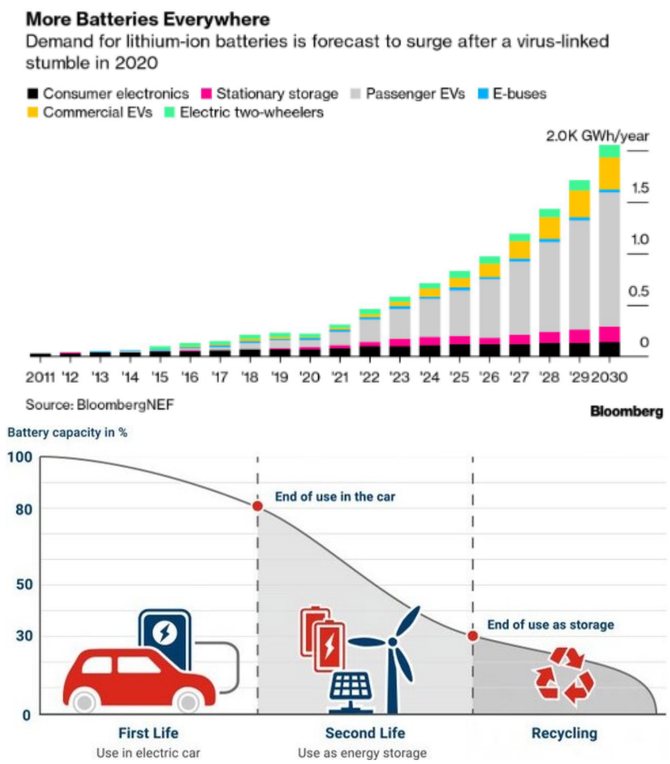


Fig. 5. Demand for lithium-ion batteries [40] and circular economy for electric vehicles including design for sustainability [41].

sustainable sources of these raw materials but maximizing the use of existing batteries is far more effective and viable considering the end-of-life EV batteries typically have as high as 80% of their original energy capacity as shown in Fig. 5.

The batteries used by EVs are suitable for stationary or industrial storage applications where the performance, space, and weight requirements are considerably less stringent than those of automotive applications. There have been multiple pilot projects demonstrating the use of EV batteries in stationary applications as shown in Fig. 6(a) and (b). There are mainly two ways of integrating EV batteries with power grid: 1) pack-level integration and 2) module-level integration. In pack-level integration, the entire EV battery pack with its original housing and battery management system is used to minimize the additional workload associated with disassembly and repackaging. In module-level integration, each battery module is disassembled from the battery pack and repackaged, as shown in Fig. 6(b). This allows more flexibility than pack-level integration in terms of voltage, power, and overall size of the system.

IV. RECYCLING AND DESIGN FOR SUSTAINABILITY

There are three different ways of recycling. In direct reuse, magnets could be removed from end-of-life motors and used again in new motors. This is, however, not a realistic option at present, as the magnets in the current EVs were not designed to be removed and are often difficult to extract. The main goal of research in [45]-[49] is to develop an alternative electrical machine topology based on Design-for-Reuse which allows an efficient recovery and reuse of PMs in new EVs. The second option is direct recycling, in which the magnets are treated as a raw material for the production of new magnets, but using novel techniques such as hydrogen decrepitation processing, plasma/strip casting, and spark plasma sintering, to give new, ready-to-use, magnetic materials or a new master alloy that can be processed using existing magnet production facilities [50]. The last option is indirect recycling. Indirect recycling implies that the magnet scrap material is transformed to its elemental components. The RE elements are recovered from the magnets and separated from each other for use in subsequent PM production.

A detailed summary of various electric machines, including power density, raw material cost, carbon footprint of major components, materials, manufacturing process, and recyclability, is shown in Table 1. Despite their high power density, PM machines have the highest material cost due to the high magnet they need. Switched reluctance machines (SRM) have the lowest raw material cost due to the amount of materials used and manufacturing simplicity. Regarding carbon footprint, the same trend as the cost is concluded, as PM machines need a high amount of RE material in their structure. The induction machine is the motor topology with a medium carbon footprint, where the reduction of the RE materials is compensated by the considerable amount of copper and/or aluminum used in this motor topology.

In terms of recyclability and sustainability, SRM and externally excited synchronous machines (EESM) show the highest capability due to their materials and manufacturing features. Compared to the RE elements, copper is not a critical raw material. The inherent properties of copper, including its durability and excellent conductivity, position it as the preferred material for advancing the green transition. Copper

TABLE 1. Comparison of Electric Machines for EVs considering Carbon Footprint and Recyclability.

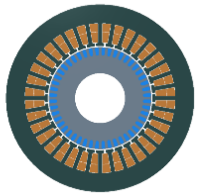
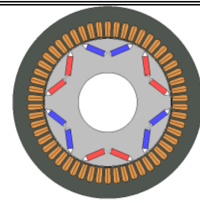
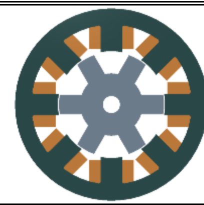
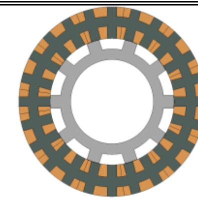
Type	Induction machine	Permanent magnet machine	Switched reluctance machine	Externally excited synchronous machines
Machine design				
Power density [51]-[54]	Medium	Highest	Low	Medium
Raw Material Cost [51]	Medium	Highest	Lowest	Low
Carbon footprint [55], [56]	Medium	High	Low	Low
Recyclability	Medium	Low	High	High
Key features and materials	- No magnets - Aluminum or copper cage bar separation - Electrical steel	- Magnet degaussing - Manual magnet separation - Copper - Electrical steel	- No magnets - Copper - Electrical steel	- No magnets - Copper - Electrical steel

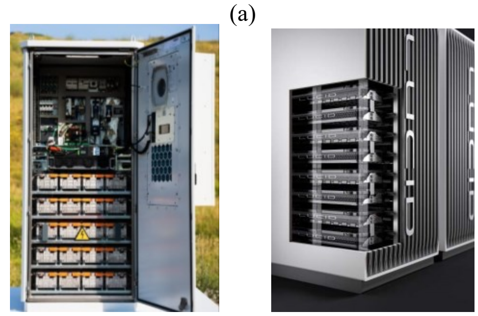
TABLE 2. ELU, CO_2, and Estimated Costs of Raw Materials Used in Electrical Machines [63]-[66].

Parameter	Unit	Material			
		RE elements	Copper	Aluminum	Laminated steel
ELU	ELU/Kg	175-1500	131	0.16	1
CO_2	CO_2/Kg	30-35	3	3.1	1.4
Cost	US$/Kg	210	8.5	2.34	2.4

holds a prominent role in various decarbonization technologies, such as electric vehicles, wind turbines, photovoltaic panels, and energy-efficient equipment. Forecasts indicate a doubling in demand for copper by 2050, rising from 25 million tonnes in 2020 to 50 million tonnes. Present estimates suggest that copper resources surpass 5 billion tonnes [57]. Therefore, copper is not considered as a critical raw material. Mining is the primary route of copper production that provides 70% of the demand; recycling, the secondary route, covers the other 30% of the total demand [58]. As a 100% recyclable material, copper can be reused repeatedly without losing its physical properties.

PM machines are the workhorse in many modern battery and hybrid electric vehicles, enabling high torque densities and efficiency. However, concerns about their long-term viability arise from RE materials high costs, limited availability, and sustainability issues in extraction and refinement. As of 2020, around 77% of the propulsion motors in BEVs and PHEVs were PM machines, with the rest divided between the magnet-free induction machines at 17% and EESMs accounting for just 6% [59]. EESMs have garnered interest in the passenger car sector in recent years due to their potential to eliminate RE magnets from their design [60]-[62]. This motor topology offers excellent efficiency under low torque and high-speed conditions, contributing to extended vehicle range, particularly during highway driving, a critical factor for customer satisfaction. However, a notable challenge associated with EESMs is the requirement for a relatively high amount of copper in its structure, posing sustainability and cost concerns. Copper ranks second in environmental impact after RE material and entails significant CO_2 emissions during extraction. Despite removing RE magnets from the motor structure, the increased copper content substantially elevates both CO_2 emissions and production costs. A comparison between environmental load unit (ELU), CO_2 emission (when materials are extracted from the earth), and cost of different materials used in electrical machines are presented in Tables 2 [63]-[66].

(a)



(b)

Fig. 6. (a) Pack-level 2nd-use ESS [41]-[42] and (b) module-level 2nd-use ESS [43]-[44].

Wound-field flux switching machine (WFFSM) is an unconventional type of EESM that is a possible candidate for research for high-power density traction applications [54]. The industry has shown a rising interest in WFFSMs due to their ability to merge the benefits of (SRMs) and (PMSMs). WFFSMs have robust rotor structures like SRMs and maintain comparable torque density as PMSMs through the flux-focusing effect. However, the doubly salient structure increases the cogging torque and odd harmonics in the terminal voltage. WFFSM, shown in Table 1, with toroidal field and armature windings, is a desirable machine design candidate, which simplifies the access of the copper at the end-of-life. Besides easier winding extraction toward a recycling process, this type of stator is relatively easy to manufacture with a high winding fill factor. It also provides better cooling because windings are directly exposed to the stator housing with a cooling jacket.

V. CONCLUSIONS AND FUTURE WORK

This paper provides a comprehensive review of past, present, and future technologies for closing the loop of circular economy in transportation electrification. As the demand for electrified transportation rapidly increases, multi-purpose use, reuse, and recyclability will become more important than the current research targets of improving efficiency, power density, and performance. Due to the high cost, limited availability, and environmental concerns of rare-earth materials, it is imperative to explore alternative technologies to replace or reduce rare-earth-based magnets in electrical machines. Highlighted are the advantages of energy savings, cost reduction, and environmental benefits associated with gathering and recycling materials in various electrical machine topologies for propulsion system applications.

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