Closing the Loop on Circular Economy in Transportation Electrification: Reuse, Repurposing, and Recycling of Batteries, 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 costlier. Furthermore, the extraction and processing of these materials produce significant carbon emissions and release harmful toxins. The economic value of the materials and components in EVs is generally 20-30% higher than that of 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.**

***Index Terms*— Carbon emission, circular economy, eco-design, end-of-life, externally excited synchronous machine, induction motor, lithium-ion battery, permanent magnet synchronous motor, recycling, rare-earth materials, sustainability, switched reluctance motor.**

I. INTRODUCTION

THE global shift toward sustainable development has become increasingly urgent. The electrified transportation industry has emerged as one of the fastest-growing sectors, particularly with the rising adoption of electrified vehicles such as hybrid electric (HEVs) and electric vehicles (EVs). However, the surging demand for EVs brings the challenge of managing materials and components at the end of their life cycle. The conventional linear economy approach leads to the disposal of these components as waste, contributing to environmental pollution and economic loss. This model also accelerates resource depletion, generates hazardous waste, and limits the potential for reuse and recycling.

The powertrain of HEVs and EVs comprises several key components, including the internal combustion engine (ICE), which provides mechanical power; the electric machine, responsible for electromechanical energy conversion; the energy storage system (battery), which stores and supplies electrical energy; and the power electronics, which control the flow of energy between the battery and motor, and other components [1]. This paper emphasizes the need to transition to a circular economy within transportation electrification, with a particular focus on batteries, power electronics, and electric machines, as illustrated in Fig. 1.

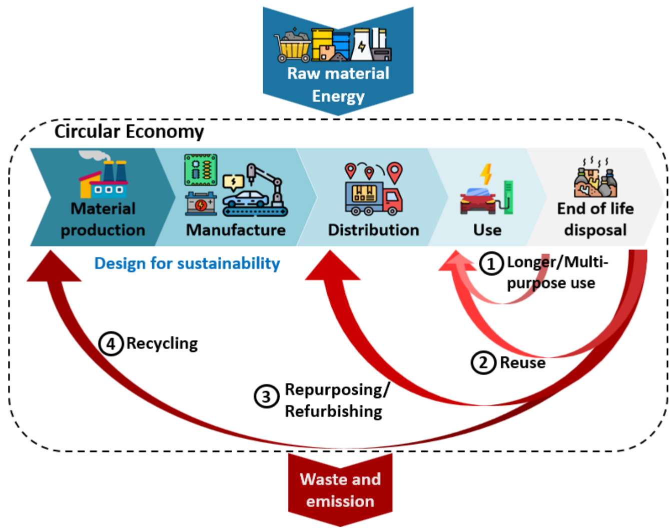


Fig. 1. Circular economy for EVs, including design for sustainability.

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 chargers [2], [3], [4], [5], [6], [7], [8], [9], multi-functional inverters for EV charging applications [10], and EV battery swapping and refurbishing [11], [12], [13].

The next 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

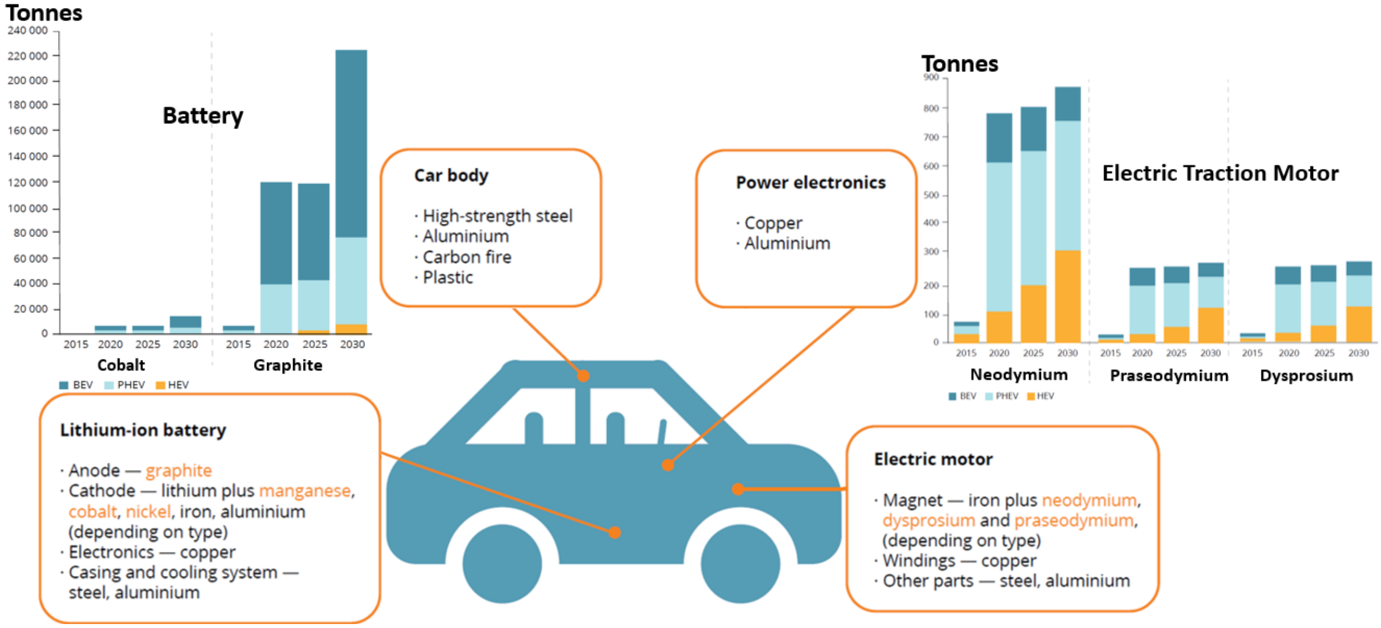


Fig. 2. Critical raw materials from EVs and demand forecasts for 2030 [23].

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 [14], [15], [16], [17], [18] and mobile [19], [20], [21], [22] applications, will be introduced in detail.

The last pillar revolves around recycling practices tailored for power electronics, electric machines, and batteries. We explore innovative recycling methods that extract valuable materials from retired components, promoting a sustainable supply chain for critical elements like rare-earth (RE) materials and reducing the overall ecological footprint of electric transportation systems. This article aims to provide an in-depth overview by exploring existing and state-of-the-art recycling technologies, as well as future trends, for batteries [23], [24], electronic components (e.g., printed circuit board (PCB)) [25], [26], [27], [28], [29], [30], [31], [32], and RE materials [33], [34], [35], [36], [37], [38].

The expected demand for critical raw materials and RE elements driven by projected EV market growth in the EU by 2030 is depicted in Fig. 2. The left bar graph highlights the demand for cobalt and graphite in EV batteries, while the right graph illustrates the demand for neodymium, praseodymium, and dysprosium in traction motors. This rising demand must be addressed through either the primary route of mining raw materials or the secondary route of recycling. While much attention has been paid to improving the performance and efficiency of electric machines, the sustainability aspects, such as carbon emissions, environmental load unit (ELU), and raw material cost of traction motors with different topologies, remain largely unexplored. The research in [39] offers a review of carbon emissions in the manufacturing of electrical machines and compares the emission values of various materials commonly used in different components of electric machines.

Fig. 3. Integration of electrified transportation system with electric power grid through charging infrastructure.

This paper aims to shed light on the neglected dimension of electric machine design by providing a comprehensive review of sustainability factors, including carbon emissions, ELU, and cost in manufacturing. By comparing the sustainability aspects of the main components of electric machines with different topologies, we significantly contribute to the broader discussion on sustainable electric machine design.

This paper advocates for a holistic approach to circular economy principles in transportation electrification, emphasizing the 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 follows. 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. This section also delves into recycling methodologies to extract valuable materials from

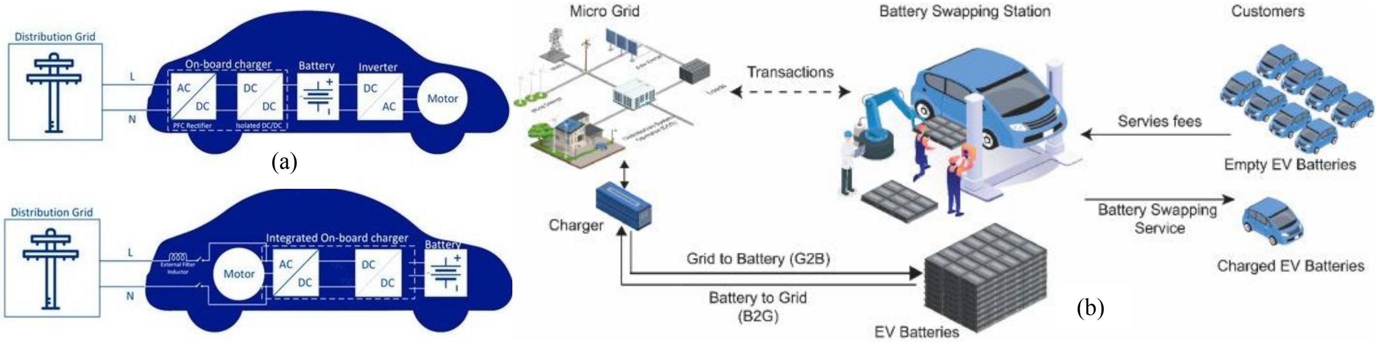


Fig. 4. (a) Concept of integrated on-board charger [42], and (b) multi-purpose use of battery swapping stations [43].

existing power electronics components at the end of their lifecycle. Section IV details the materials used to make the various parts of the electric machines. The sustainability aspects of electric machines, including carbon emissions, ELU, and costs, are quantified using established equations and data from the literature review. Additionally, it will explore alternative electrical machine topologies based on design-for-reuse, which allows for the efficient recovery and reuse of its components. Lastly, the conclusion highlights key findings and their implications, underscoring the contributions of this study.

II. LONGER AND MULTI-PURPOSE USE

The concept of longer and multi-purpose use in transportation proliferates due to 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 a 5% utilization factor [42]. From a sustainability perspective, increasing the utilization factor to its maximum is critical 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.

A. Integrated On-Board Charger

Integration of on-board charger (OBC) with the propulsion system [2], [3], [4], [5], [6], [7], [8], [9], [10] is one way of maximizing the power electronics and electric machine utilization factors, as shown in Fig. 4 (a). Integrated OBCs often use inverter power electronics and motor windings to perform AC-DC conversion for charging. This repurposing means that the inverter, which is typically only used while driving, now has an additional charging function, increasing its operational time and utilization.

B. Grid Integrated Battery Swapping Stations

It has also been reported that battery swapping stations (BSSs) for EVs can be utilized as stationary energy storage systems (ESSs) to support the power grid, as shown in Fig. 4(b) [11], [12], [13]. The batteries in BSSs serve as an ESS, supplying power to mobile or stationary loads during grid outages or renewable energy source downtimes. The non-dispatchable nature of renewable energy often leads to supply-demand mismatches, causing fluctuations. These fluctuations can be managed by integrating BSSs with the grid, where the BSS not only provides swapping services for EVs but also contributes services to the grid [44]. By offering cost-effective electricity during peak hours or periods of non-availability, BSSs demonstrate up to a 35% reduction in consumer electricity costs during peak hours and an 8.8% reduction in overall costs during 24-hour operation [45].

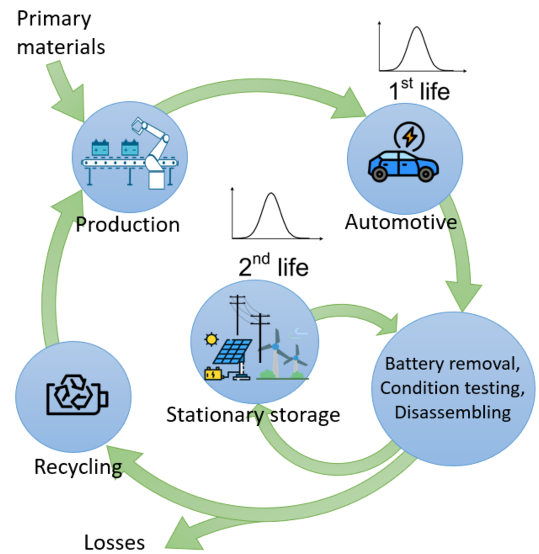


Fig. 5. Simplified closed-loop system for EV batteries [40], [41].

III. REUSE AND REPURPOSING

Since lithium-ion batteries were introduced to the market in the early 1990s, their demand has steadily increased due to their high energy density and superior performance. This trend has been primarily driven by the electrification of transportation, which accounts for over 60% of the total demand. However, the surge in battery demand has raised concerns about the long-term availability of raw materials and waste management. While finding sustainable sources for these materials is crucial, maximizing the use of existing batteries is a more effective and viable solution.

A simplified life cycle of EV batteries within a circular system is depicted in Fig. 5. Depending on the degree of disassembly and the condition testing, these batteries can either

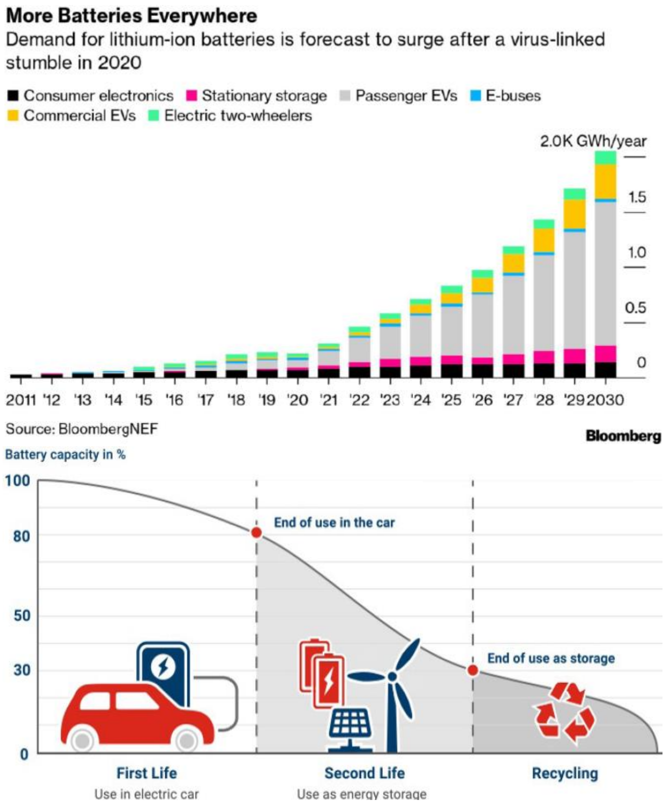


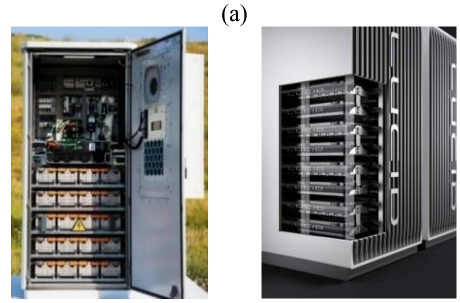
Fig. 6. Demand for lithium-ion batteries and circular economy for EVs including design for sustainability [46].

be repurposed for second life applications or sent for recycling. When electric vehicle (EV) batteries degrade to around 80% of their original capacity, they are typically considered unsuitable for electric mobility, marking the end of their first life. These batteries can be repurposed for various second life applications, including renewable energy systems, energy storage, fast charging facilities, peak shaving, and residential building infrastructure until their capacity diminishes to approximately 30% [46], [47].

The lifespan of second life batteries varies significantly depending on their use, ranging from around 6 years in grid and off-grid stationary applications to up to 30 years in mobile applications, such as supporting EV charging stations and powering small electronic devices [40], [47]. Proper management, such as maintaining optimal charge levels and avoiding deep discharges, can significantly extend the lifespan of second life batteries. Additionally, advancements in battery management systems for second life applications are improving their durability and reliability. Projections indicate that global second life battery capacity will grow from 55 GWh in 2024 to approximately 953 GWh by 2030 [48]. Ultimately, once these batteries can no longer store energy effectively, they are directed to recycling, as illustrated in Fig. 5 and Fig. 6. Details of the EV battery recycling process are discussed in the following section.

EV batteries are well-suited for stationary or industrial storage applications where performance, space, and weight requirements are less stringent than in automotive applications. Numerous pilot projects have demonstrated the use of EV batteries in stationary applications, as shown in Fig. 7 (a) and

(a)



(b)

Fig. 7. (a) Pack-level 2nd-use ESS [49], [50] and (b) module-level 2nd-use ESS [51], [52].

(b). There are two main methods for integrating EV batteries with the power grid: 1) pack-level integration and 2) module-level integration. In pack-level integration, the entire EV battery pack, including its original housing and battery management system, is used to minimize additional work related to disassembly and repackaging. Each battery module is disassembled from the pack and repackaged in module-level integration, as shown in Fig. 7 (b). This method provides greater flexibility regarding voltage, power, and overall system size compared to pack-level integration.

This integration leads to module cost savings by reducing inventory costs, replacement costs, and other components. Additionally, the high-energy density characteristic of EV batteries allows more energy to be stored in a container than conventional energy storage modules. Second life batteries also offer additional societal benefits. From a carbon perspective, one MWh of second life batteries represents approximately 450 metric tons less embodied carbon than one MWh of first-life batteries [53]. This reduction in carbon intensity mainly comes from manufacturing processes. However, the two primary lithium extraction methods also have considerable environmental impacts: brine extraction requires about half a million gallons of water to produce enough lithium for a megawatt-hour of lithium iron phosphate batteries, while hard rock mining is highly energy-intensive. Both methods can also result in pollution, contaminating groundwater and surface water with toxic chemicals and acid mine drainage [53], [54].

EV batteries are designed for high range and high-power performance rather than cyclic lifetimes. Still, this optimization does not align well with the high cyclic lifetime requirements of energy storage systems, mitigating their advantages. Additionally, cost benefits are not as significant because second life batteries incur expenses from direct replacement costs and installation, transportation, and system downtime. Moreover, the battery management system (BMS) in EV batteries must be updated when battery modules are repurposed for second life applications. Liability is a crucial consideration for second life batteries. The varying lifetimes of connected battery modules in these applications necessitate a new safety standard. The

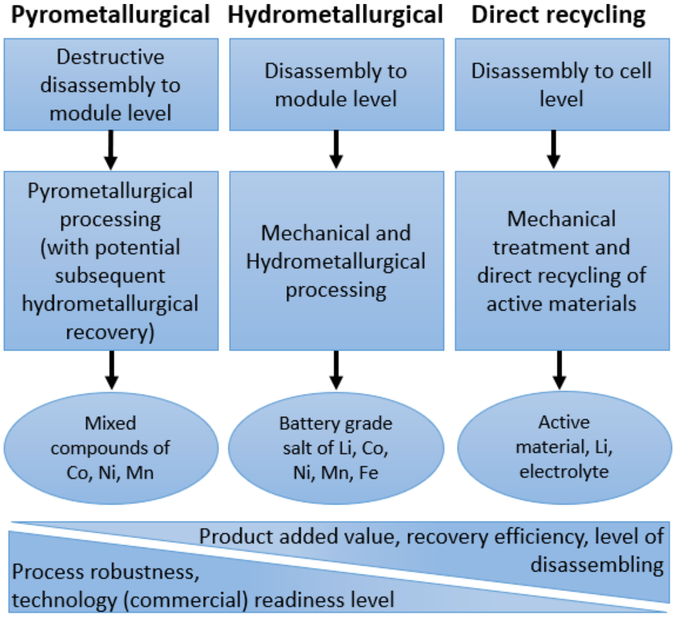


Fig. 8. Basic structure of possible technologies for the recovery of lithium-ion batteries [41], [61].

existing test standard, IEC 62933-5-3, does not account for adapting testing standards to include battery systems made from used components. It does not address how the varying quality of used batteries affects testing representability [55].

IV. Recycling

By 2050, the annual generation of waste electrical and electronic components is projected to reach 120 million tons, given the current reuse and recycling rates, which remain relatively low (e.g., less than 20% of e-waste is currently collected and recycled) [56], [57]. Within the circular economy paradigm shift, recycling should be integrated into the product lifecycle, following stages such as multi-purpose use, reuse, and refurbishing.

A. Recycling of Batteries

From 2023 to 2040, global demand for lithium will grow 870%, 210% for nickel, 390% for graphite, and 220% for cobalt. Due to this surge, it is anticipated a parallel growth in the battery recycling industry through several distinct, potentially non-competitive technologies [58]. As discussed earlier, battery systems with energy capacities below 80% are no longer suitable for use in EVs. Depending on the degree of disassembly and the condition testing, these batteries can either be repurposed for second life applications or sent for recycling. The modules or individual cells that are still well-functioning can be extracted from the battery pack and start the second life in alternative applications with less restricted performance requirements, such as stationary energy storage.

Ultimately, EV batteries must be recycled after their first or second life. In this process, an attempt is made to recover as many components of a lithium-ion battery as possible as raw materials for new batteries. Before the batteries are dismantled into their individual parts, they must be completely discharged. This is done to avoid the risk of dangerous contact voltage or fire and to use the residual energy that is still stored in the battery [47].

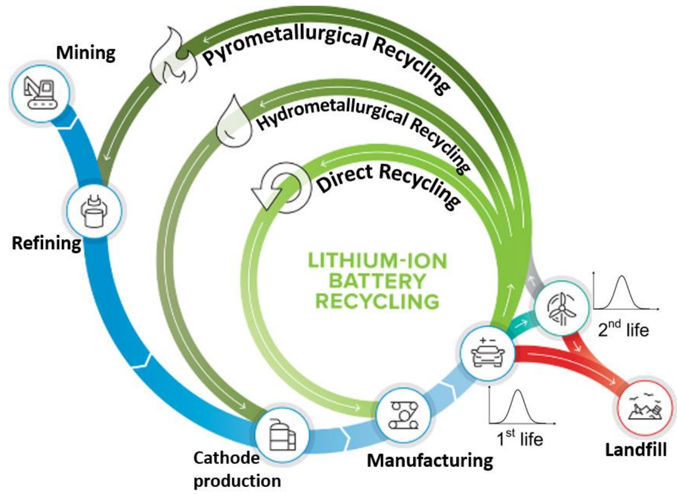


Fig. 9. Schematic representation of various recycling technologies within the lifecycle of a lithium-ion battery [62].

Various technologies are utilized for recycling lithium-ion batteries, including pyrometallurgical, hydrometallurgical, and direct methods, as well as their combinations, each offering distinct benefits and drawbacks. The basic principle of these three technologies is presented in Fig. 8. The first, pyrometallurgical recycling (smelting), is designed to process various battery chemistries in a single step, focusing on recovering valuable metals like cobalt, nickel, and copper. However, materials like aluminum and lithium often end up in slags and are not typically recovered due to economic reasons. The overall metal recovery, particularly lithium, is less than that achieved with alternative methods. The mixed metal fraction obtained from this process, containing cobalt, nickel, copper, and iron, can be repurposed for alloy production [41]. Subsequent hydrometallurgical treatment is then required to refine the metals for battery manufacturing. Pyrometallurgical recycling is currently the dominant industrial recycling technology for lithium-ion batteries [41], but it is energy-intensive and has the highest environmental impact [59], [60].

The second approach, hydrometallurgical recycling, is the best available technology due to its high mineral recovery rates and relatively low environmental footprint [59]. It uses liquid solutions to separate minerals. This method uses liquid solutions to separate minerals and requires detailed disassembling and careful sorting of battery chemistries to avoid contamination. Although it is resource-intensive regarding the use of several reagents for hydrometallurgical treatment, this technique can recover cathode materials, battery-grade lithium carbonate, and a significant portion of aluminum [41], [59].

The third category, often referred to as direct recycling, involves processes tailored to specific battery chemistries. These methods aim to recover active materials directly, enabling their immediate reuse in cell production. The Schematic representation of the three recycling technologies within the lifecycle of a lithium-ion battery is depicted in Fig. 9. Direct recycling is energy-efficient, resource-saving, and

TABLE. 1. COMPARISON OF FEATURES ACROSS VARIOUS LITHIUM-ION BATTERY RECYCLING TECHNOLOGIES [41], [58], [59], [60], [62], [70], [71], [72].

Recycling method	Pyrometallurgical (Smelting)	Hydrometallurgical (Leaching)	Direct recycling
Maturity of the method	Commercial	Pre-commercial to commercial	Lab to pre-commercial
Environmental impact	Highest	Medium	Lowest
Energy intensity	Highest	High	Lowest
Material recovery rates	Nickel and cobalt recovered in alloy, relatively low lithium recovery	90-99% nickel, cobalt, lithium, and manganese	90% nickel and cobalt, 50% lithium
Key Players/Companies	Redwood Materials, Sumitomo, Umicore, Ecobat Solutions	Ascend Elements, Li-Cycle. Cylib, American Battery Technology (ABTC)	ReCell Center, Lohum, Princeton NuEnergy, Li Industries, OnTo Technology

highly effective but demands homogeneous cell chemistries for optimal results [41], [59]. The advantages and disadvantages of each method, along with the companies actively involved in each recycling technology, are summarized in Table 1.

B. *Recycling of Power Electronics*

As a critical element of all electrical and electronic devices, waste printed circuit boards (WPCBs) are a key focus for treating waste electrical and electronic equipment, including devices like inverters, control units, and power distribution boxes. The recycling process of WPCBs involves pre-processing and deep treatment stages. During pre-processing, electronic components are removed from the surface of the WPCBs. Various separation methods, such as mechanical, pyrogenic, pyrolysis, wet, and bioleaching techniques, have been developed to reclaim raw materials from bare PCBs [25], [26], [63], [64], [65], [66], [67], [68], [69]. Additionally, WPCBs are treated with a stripping solution to dissolve precious metals, typically gold, silver, and platinum, when the electronic components are damaged. These components can be reused and resold if they remain undamaged.

The conventional method for recycling WPCBs includes manually disassembling, acid washing in a container for precious metals recovery, or removing plastic by open burning. Then, Smelting, electrolysis, and hydrometallurgical processes were applied to refined metals, as shown in Fig. 10. The process begins with disassembly, which is carried out by heating and manually separating electronic components [65]. While this method is straightforward, it suffers from low efficiency, operator safety concerns, and significant environmental pollution due to the release of toxic gases [66]. Following disassembly, precious metals can be recovered using one of two methods: acid washing or hydrometallurgy. In the acid-washing method, electronic components are immersed in a solution to dissolve the precious metals. Once dissolution is complete, heat is applied to remove excess acid, releasing toxic gases, and the precious metals are collected afterward.

Regarding the hydrometallurgy process, the first step after disassembling is open burning. The uncontrolled disassembly temperature causes the damage of usable components and the decomposition of non-metallic materials to produce toxic gases. Plastics in the WPCBs can be effectively removed from this process, and a metal-rich residue can be obtained. Afterward, smelting is needed to transform metal-rich residue into rough metal plates. Then, these metal plates are used for electrorefining to remove copper. The anode slime, which contains the precious metals, undergoes a hydrometallurgy process to obtain the noble metals [64].

Since the conventional method of recycling WPCBs contains demerits like usable component damage due to temperature in disassembly, release of toxic gases to the operators, etc., research is being conducted to find more effective ways of recycling [63], [65]. The integrated process of recycling of WPCB/ECs with clean and cost-effective methods is shown in Fig. 11. In this method, the basal plate and ECs are separated first. Some common methods include heating, mechanical grinding, and chemical dissolution [67]. After that, various ECs are sorted out. Unique tests should be performed for each component to check whether it can be reused [68]. Most power electronic PCBs in EVs include components like power inductor cores and heat sinks. These components can be reused if a PCB has not undergone physical damage. Then, the damaged electronic components and basal plates undergo mechanical crushing, pyrolysis, or supercritical flow processes to reduce the size of the raw materials. Afterward, electric, magnetic, pneumatic, or froth flotation is performed to separate metals and non-metals. Research findings have shown that the non-metallic part of a PCB can be around 65%-70% of its weight [65]. Finally, hydrometallurgy, thermo-metallurgy, etc., is used to extract precious metals, while non-metal parts can be further recycled by using this process [69].

Another way to create a circular economy concept for EV vehicles is by manufacturing the basal plate of the power electronic circuits using recyclable materials. Typically, these PCBs are made of epoxy resin with glass fiber reinforcement, which makes them difficult to recycle [65]. A polymer called Vetrimer is used to replace the resin and create new PCBs that can be recyclable and reusable. When such a PCB becomes unusable, tetrahydrofuran solvent can be used to dissolve the Vetrimer and obtain the undamaged components. Moreover, findings indicate that 98% of Vetrimer and 91% of the solvent can be used again [73], [74].

There is an increasing trend of using artificial intelligence (AI), machine vision, and automation in PCB disassembling

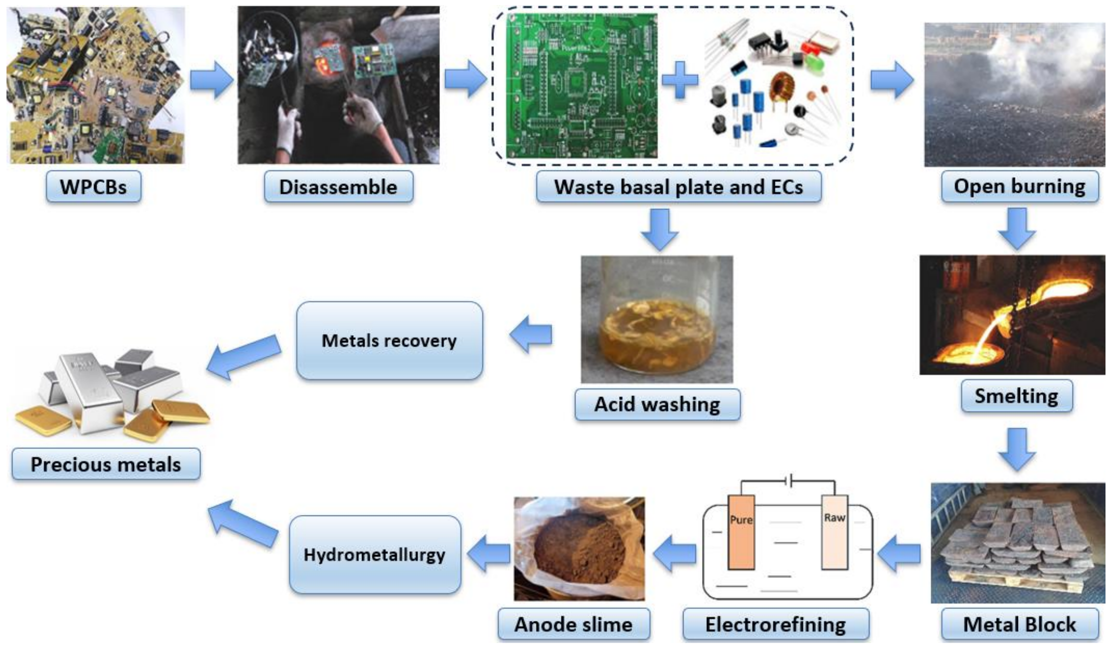


Fig. 10. The Schematic of conventional smelting-based or acid-washing recycling of WPCBs and components [63], [64].

process. An automatic system for efficient disassembling of electronic components is recorded in [75]. In this system, the primary machine in the cell is a commercial Lead-free soldering system. Apart from that, it has a two-axis manipulator with a vacuum gripper to extract electronic components from the PCB and a central control unit to manage and automate. The wave soldering system was reconfigured for desoldering. After manually loading the PCB onto a conveyor, it moves over a preheating plate. Then, the molten metal wave desolders the connections. Finally, the manipulator plucks the components safely. According to the results, the system could remove 450 microprocessors from 50 boards without damaging them and allow them to be reused without additional processing. Moreover, it was tested up to the desoldering of multiple SMD components, including up to nine microprocessors, within a total time of 137 seconds.

AI and machine vision are utilized to classify electronic components in [76]. This method has an accuracy of 80%, and more precious metals can be recovered than traditional methods. The experimental setup in this work has two hardware platforms. One hardware platform is for model building and the other one is for deployment. This was done due to the significant computational effort required at various stages. The selected software solution utilizes YOLOv5, a real-time object detection system based on convolutional neural networks. Moreover, this model was extended using transfer learning to recognize selected electronic components directly on the board. It enabled the detection of electronic components like resistors, electrolytic capacitors, non-electrolytic capacitors, inductors, and ICs.

Several strategies can be implemented to create a circular economy for power electronic boards and components. Recycling and reusing are needed to reduce the number of heavy metals and toxic materials entering the environment. Efficient and safe removal of electronic components can be

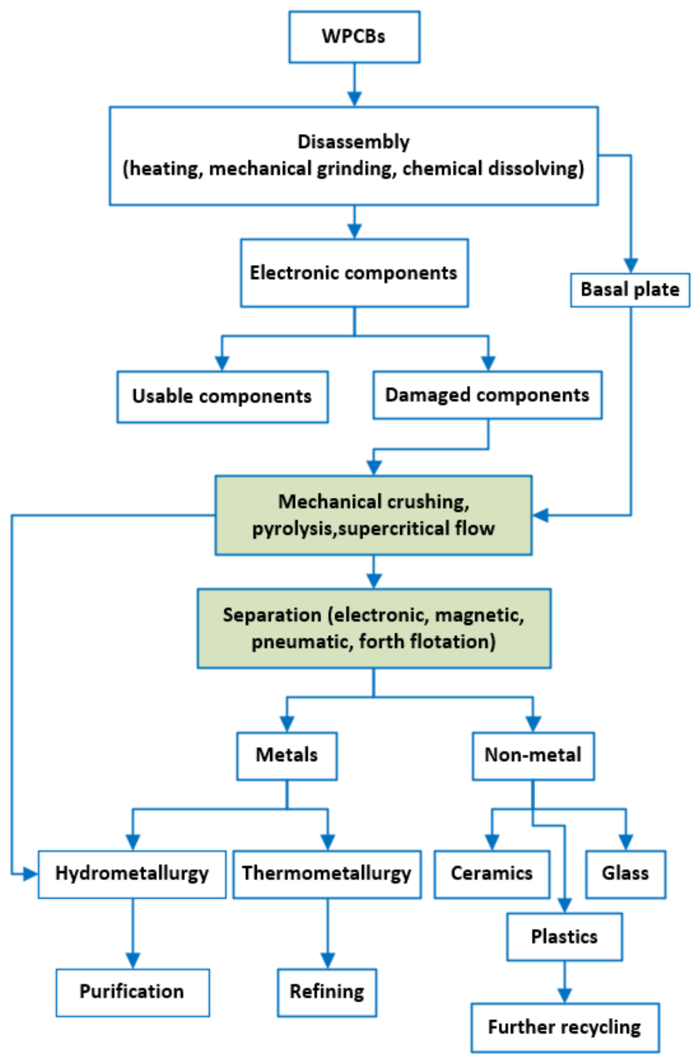


Fig. 11. Clean and cost-effective integrated recycling process for WPCB/ECs, featuring mechanical crushing and precise material separation [63].

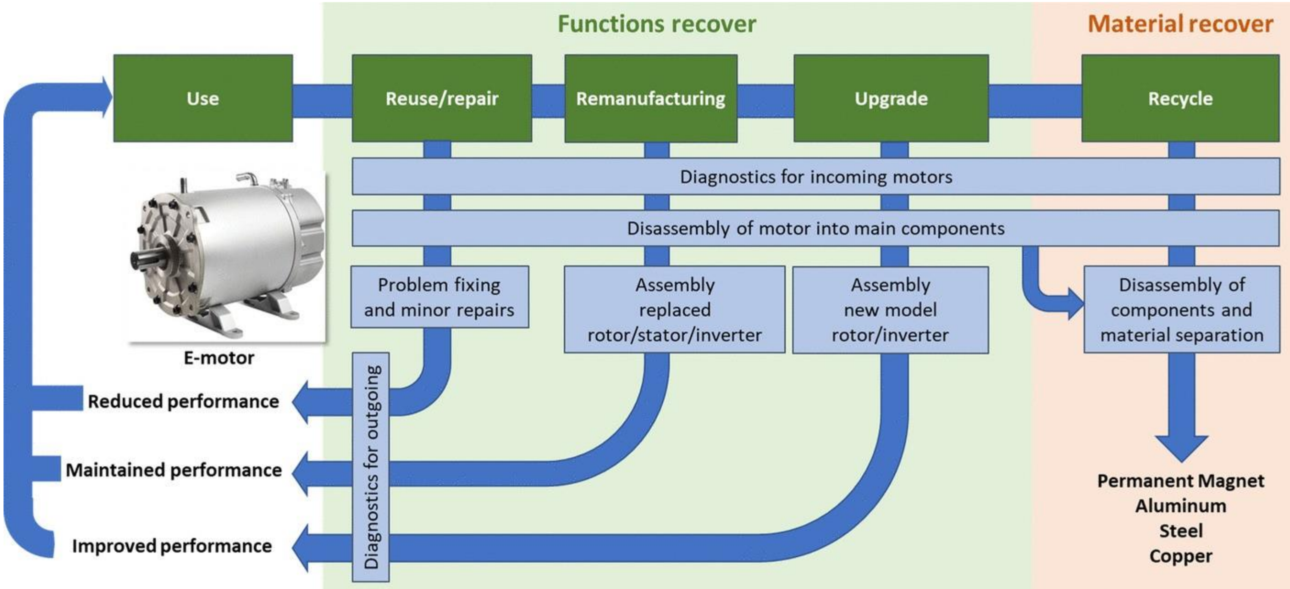


Fig. 12. Framework for the circularity of electric machines [77].

achieved by utilizing novel recycling methods. These involve advanced disassembly techniques such as mechanical grinding, chemical dissolution, and automated systems incorporating AI and machine vision. Innovative materials also play a crucial role. Manufacturing PCBs using recyclable materials rather than conventional epoxy resin allows for the PCB to be dissolved and the components can be recovered and reused. This significantly improves the recyclability of the components. Automation and AI enhance the efficiency and safety of recycling processes. Automated systems for disassembling and classifying electronic components, utilizing techniques such as real-time object detection and transfer learning, improve the accuracy and speed of component identification and recovery. Integrating these strategies into the industry can make power electronic boards and components sustainable. It will enhance the circular economy while minimizing waste and maximizing resource recovery.

C. *Recycling of Electric Machines*

A graphical representation of the circularity for electric machines is depicted in Fig. 12, summarizing the possible circular loops for the reuse, remanufacture, upgrade, and recycling of electric machines with respect to the involved components. Function recovery, also known as value retention, aims to maximize the functional value of electric motors by promoting reuse, remanufacturing, and upgrades [77].

Recycling involves the process of converting material that would otherwise be considered waste, into materials for different products. The electric machine is dense with aluminum, steel, copper, and RE magnets (where used), which can find application in several different products. In this case, the electric machine should go through complete disassembly/crushing operations before being dismantled and materials recovered. Several processes, from mechanical to chemical, are needed. Disassembly of electric motors may include operations such as unscrewing, disassembling components from the case, extraction of PMs (if present), separation of windings from the main stator core, and disassembling of shafts. Whereas all these operations can be performed manually, the quest for making the circularity of electric machines a competitive business approach requires a push for full or partial automation.

The disassembly of PMs from motors must be addressed quite carefully. Moreover, such disassembly strategies change with the type of electric machines. In the case of IPM, their extraction can be performed with rotor-specific ejectors that press out the magnets from their rotor segments, while in SPM, the rotor needs to be freed of the bandages before magnet extraction. Removal of the bandage needs thermal softening of the glue. Then, the magnets are shorn off with a nonmagnetic wedge [77], [78]. With respect to recycling, the main issues concern the separation of different RE materials and, later, the remanufacturing of PMs according to the specific recipe. For raw material recovery, various approaches and processes have been developed in recent years, which can be classified into gas-phase extraction, pyrometallurgical methods, and hydrometallurgical methods such as hydrogen decrepitation, sintering, machining, and coating [77], [78], [79].

V. Sustainability Aspects of Electric Machines

The electric machine in the traction system is used to convert the electrical energy into mechanical motion and vice versa. The growing dependence on electric machines in the sector necessitates a thorough design approach that extends beyond their operational phase. While efficiency improvements are a primary focus, it is crucial also to consider the environmental impact of the manufacturing processes [80], [81], [82], [83], [84]. Carbon emissions from raw materials can account for up to 90% of the total emissions during the manufacturing phase of electric machines [39]. This section aims to concisely calculate and compare the carbon emissions and ELU of the active and passive components across various electric machine topologies used in traction applications. By systematically evaluating these results, we can provide valuable insights for

TABLE. 2. CARBON EMISSION FACTORS, ENVIRONMENTAL LOAD UNIT, AND ESTIMATED COST OF RAW MATERIALS COMMONLY USED IN ELECTRIC MACHINES

Component	Active components					Passive components				Reference
	Winding		Magnet		Lamination	Housing	Shaft	Bearing	Insulation	
Material	**Cu**	**Al**	**NdFeB**	**SmCo**	**Silicon steel**	**Al alloy**	**Carbon steel**	**Chrome steel**	**Aramid**	
Carbon emission factor [$KgCO_2/Kg$]	4	9	25	60	2	8	3	2	11	[39], [85]
Environmental load unit [ELU/Kg]	131	0.16	200	1200	1	0.16	1	1	-	[86], [87]
Cost [US$/Kg]	8.5	2.7	50-210		2.4	2.7	0.8	12.4	-	[88], [89], [90], [91]

electric machine designers and encourage more sustainable and environmentally conscious practices within this industry.

A. *Carbon Emission of Electric Machines Raw Materials*

This subsection outlines the carbon emission factors associated with commonly used materials for both active and passive components in electric machines. Active components, such as windings, soft magnetic materials, and magnets, are crucial for energy conversion. Selecting the appropriate core, magnet, and winding materials for active components is vital, as the efficiency of the electric machine is closely linked to the energy losses from these parts. Passive components include the housing, shaft, bearings, and insulation systems, where the main considerations are the physical and structural properties of the materials. In terms of carbon emissions, the total emission value of a material increases with both its mass and its carbon emission factor. Table 2 lists the average carbon emission factors for materials commonly used in active and passive components of electric machines. The carbon emission factors considered here would represent the average if the literature review provided a range of values for each material. The emission factors in this paper are based on the cradle-to-gate approach, which covers the production stages from raw material extraction (cradle) to the point when the materials leave the factory (gate).

Winding Materials

Windings are used to induce electro-motive force and produce a rotating magneto-motive force in electric machines. Copper is the most commonly used material for motor windings due to its excellent electrical conductivity, though it has a higher mass density. Aluminum, another winding material, emits 9 $KgCO_2/Kg$ on average, which is more carbon-intensive than copper, which has an average emission factor of 4 $KgCO_2/Kg$. The key factor influencing the embodied carbon emissions of aluminum is the carbon intensity of the electricity used, as aluminum production requires high temperatures and significant energy for the electrolysis process. Copper, on the other hand, often relies on ore that requires less refining and less energy-intensive extraction processes. This translates into higher carbon emissions for aluminum compared to copper for the framework of the cradle-to-gate [92], [93].

Magnets

Magnets play a crucial role in electric machines as a source of flux. Amongst the RE PMs, NdFeB is the most powerful available magnet, with an average carbon emission factor of 25 $KgCO_2/Kg$. SmCo magnets, while comparable in strength to NdFeB, offer superior temperature stability and coercivity but emit 60 $KgCO_2/Kg$.

Lamination

Silicon steels, containing approximately 2% silicon, are the most used soft magnetic materials for lamination. These steels have an emission factor of 2 $KgCO_2/Kg$.

Passive Components

This part covers the various materials used in the passive components of electric machines, such as housing, shaft, bearing, and insulation. Aluminum alloy, known for its high machinability, strength, durability, lightweight nature, and recyclability, is the most widely used material for machine housings with average carbon emission factors at 8 $KgCO_2/Kg$. Carbon steel and chrome steel, commonly used for shafts and bearings, have 3 and 2 $KgCO_2/Kg$ carbon emission factors, respectively. The insulation system has different parts and materials to meet the requirements for turn-to-turn, phase-to-phase, and phase-to-ground insulation. In this study, only aramid is considered as wire insulation with a carbon emission factor of 11 $KgCO_2/Kg$.

B. *Environmental Load Unit of Raw Materials*

Environmental load unit (ELU) is a standardized measure used to quantify the environmental impact of various activities, products, or services in financial terms. One ELU represents the environmental damage cost equivalent to one Euro [94]. They encompass factors such as resource consumption, emissions, and ecological degradation, translating these diverse impacts into a common metric for easier comparison and assessment. By integrating multiple dimensions of environmental stress, ELUs facilitate more comprehensive and meaningful evaluations of sustainability efforts. A comparison between ELU of different materials used in electric machines is presented in Table 2. Among different materials used in electrical machines, RE magnet materials and copper are considered as the ones with the highest ELU. An estimated cost of raw materials commonly used in electric machines is also presented in Table 2.

C. *Carbon Emission Measurement of Electric Machines with Different Topologies*

Four typical traction motor topologies have been selected in this study, including an induction motor (IM), an interior permanent magnet synchronous motor (PMSM), a switched reluctance motor (SRM), and an externally excited synchronous motor (EESM). As of 2020, around 77% of the propulsion

TABLE 3. THE BASELINE TESLA MODEL S INDUCTION MOTOR SPECIFICATION [105].

Parameters	Value
Stator outer diameter (D_{OS})	254 mm
Stator inner diameter (D_{IS})	156.8 mm
Rotor outer diameter (D_{OR})	155.8 mm
Rotor inner diameter (D_{IR})	50 mm
Stack length (L_{st})	152 mm
Airgap length	0.5 mm
Output power	225 Kw
Output torque	430 Nm
Efficiency	93 %
Power factor	0.85

motors in BEVs and PHEVs were PM machines, with the rest divided between IMs at 17% and EESMs accounting for just 6% [95]. EESMs have garnered interest in the passenger car sector in recent years due to their potential to eliminate RE magnets from their design [96], [97], [98]. This motor topology provides high efficiency at low-torque and high-speed conditions, enhancing vehicle range, especially during highway driving, which is crucial for customer satisfaction. However, a significant issue with EESMs is their need for a relatively large amount of copper, raising sustainability and cost concerns. The SRM is well-known for its cost-effectiveness, durability, and fault tolerance [99]. However, it has intrinsic drawbacks, such as lower torque density, high torque ripple, and acoustic noise. These characteristics make SRM suitable for off-road applications [100], [101], [102], [103], [104]. Additionally, the absence of RE PMs and the robust rotor design enhance environmental friendliness and physical durability, supporting product designs for the circular economy.

The baseline traction motor examined in this research is the 3-phase 4-pole induction motor found in the Tesla Model S, featuring a 60-slot stator and a rotor with 74 bars (referred to as 60/74 IM) [105]. Key specifications of this motor are outlined in Table 3. Its squirrel cage is constructed from pure copper. Other electric motor designs considered in this study are a PMSM motor with a 60-slot 6-pole configuration, a 12/8 SRM, and an EESM with a 60-slot 8-pole setup. To ensure a fair comparison among all four motor types being analyzed and to simplify without sacrificing accuracy, the following assumptions are made:

- All traction motors share identical geometry, such as having the same stator outer diameter and stack length, as depicted in Fig. 13.
- All traction motors utilize common materials for both active and passive components. The materials used for winding, lamination, housing, shaft, and bearing are as follows: pure copper, silicon steel, aluminum alloy, carbon steel, and chrome steel. Additionally, NdFeB magnets are employed in PMSM motors.
- Traction motor insulation system has different parts and materials to meet turn-to-turn, phase-to-phase, and phase-to-ground insulation requirements. For carbon emission calculation simplification in this research, only aramid is considered as wire insulation, which is proportional to the total copper weight of the motor.

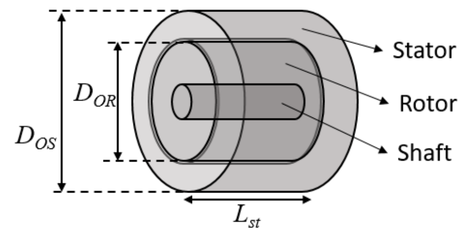


Fig. 13. Simplified geometry of electric machine components.

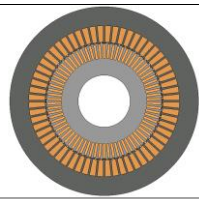
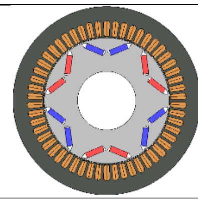
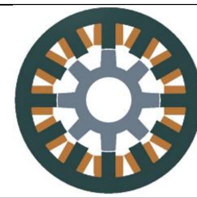
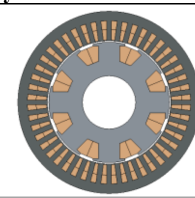
- A per-unit (PU) system is employed to quantify the volume of each component in traction motors, with the components of the IM serving as the base unit quantity. The volume of components in other motor topologies is normalized and expressed as per unit of the corresponding IM component.
- The carbon emission factors considered here would represent the average if the literature review provided a range of values for each material.
- All traction motors are made of virgin materials rather than recycled materials.

A comprehensive summary of this comparative study, including active and passive components per unit volume, total weight, total carbon emissions, ELU, total cost of raw materials, recyclability, power density, torque density, efficiency, key features, and the companies that utilize/make the traction motor topology, is provided in Table 4 [106], [107], [108], [109], [110], [111], [112], [113], [114]. Regarding material weight, IM has the highest weight, 45 Kg. This is mainly due to the high amount of steel lamination and copper used in these motor topologies. However, the motor topology with the lowest weight is EESM with 40.6 Kg due to the rotor saliency and lower need for steel in the rotor.

The total carbon emissions for each component are calculated by multiplying the material mass with the carbon emission factor. Despite its high efficiency and power density, PMSM shows the highest carbon emission of 170 Kg CO_2, mainly due to the high amount of RE magnet it needs. After PMSM, the IM has the second rank in carbon emission with 132 Kg CO_2 due to the huge amount of copper used in this motor topology. The reduction of the RE materials is compensated by the considerable amount of copper used in this rotor topology. SRM has the lowest carbon emission, with 117 Kg CO_2, due to the amount of materials used.

In terms of ELU, the IM shows the highest one with 1078 ELU, which is 8% higher than that of the PMSM (993 ELU). After NdFeB, copper has the highest ELU when mining this metal from the earth. As a result, a considerable amount of copper used in the IM topology leads to the highest amount of ELU. The PMSM ranks second in ELU due to the presence of RE materials in its rotor topology. The SRM has the advantage of the lowest ELU with 582 ELU. The same trend as the carbon emission is concluded regarding the raw material cost. Therefore, the PMSM is the most expensive topology as PM machines need high RE material in their structure. SRM is the cheapest solution due to the low amount of copper in its

TABLE 4. Comparison of Electromagnetic Performance and Sustainability Aspects of Electric Machines with Different Topologies for EV Traction.

Type	Induction machine	Permanent magnet machine	Switched reluctance machine	Externally excited synchronous machines
Machine design				
Stator core volume [p.u.]	1	1	1.1	1
Rotor core volume [p.u.]	1	0.76	0.94	0.63
Winding volume [p.u.]	1	0.51	0.52	0.78
PM volume [p.u.]	0	1	0	0
Insulation volume [p.u.]	1	0.51	0.52	0.78
Housing volume [p.u.]	1	1	1	1
Shaft volume [p.u.]	1	2.1	1	1
Bearing volume[p.u.]	1	1	1	1
Total weight [Kg]	45	42.8	42.7	40.6
Total carbon emission [$KgCO_2$]	132	170	117	119
ELU [ELU]	1078	993	582	845
Raw materials Cost [US$]	184	358	155	157
Recyclability	Medium	Low	High	High
Power density	Medium-High	High	Medium-High	Medium
Torque density	Medium	Highest	Medium	High
Efficiency [%]	93 %	96 %	89 %	95 %
Key features	- No magnets -Copper cage bar separation	- Magnet degaussing - Manual magnet separation - Copper	- No magnets - Copper	- No magnets - Copper
Vehicle/Company	Tesla S, Mercedes-Benz EQC, Audi e-tron	Tesla, Ford, Chevrolet, Nissan, Toyota, Hyundai, VW, Honda	Turntide, Enedym	BMW iX M6, Renault ZOE, ZF, Mahle

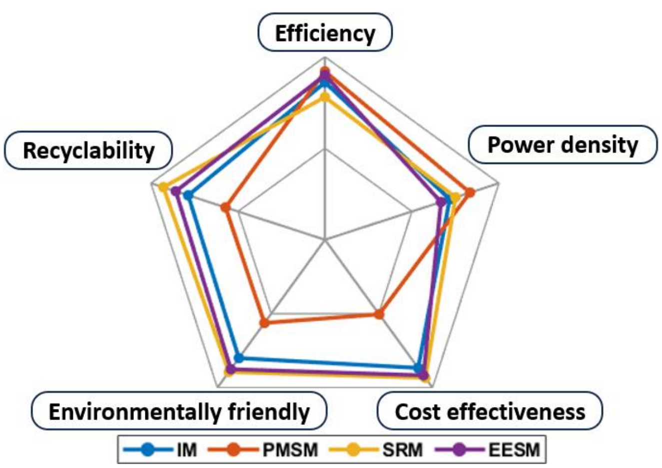


Fig. 14. Comparison of Electromagnetic Performance and Sustainability Metrics for Different Electric Machine Topologies. Higher Values Represent Superior Performance Across All Criteria.

structure.

From an electromagnetic performance perspective, PMSMs tend to have the highest torque density and efficiency due to the presence of RE magnets. In contrast, IMs and SRMs offer competitive performance characteristics at a lower cost and with greater overloading and high-speed capability. IMs can exhibit high peak torque, while SRMs have generally been less appealing for traction applications due to their lower power, torque, and efficiency characteristics. Fig. 14 presents a spider graph comparing the normalized metrics of electromagnetic performance and sustainability for the baseline IM, PMSM, SRM, and EESM. The electromagnetic performance metrics include efficiency and power density, while the sustainability metrics encompass cost-effectiveness, environment-friendliness, and recyclability. In this graph, higher values indicate better performance across all metrics.

In terms of recyclability and sustainability, SRM and 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 holds a prominent role in various decarbonization technologies, such as EVs, 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 [115]. 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 [115]. As a 100% recyclable material, copper can be reused repeatedly without losing its physical properties.

D. *Electric Machine Design for Sustainability*

The typical 1000 hp electric machine is up to 98% recyclable, by weight, with most of the materials used to manufacture it comprising of steel, copper, aluminum, and plastic composites [116]. There are three different ways of recycling. In direct reuse, magnets could be removed from end-of-life electric machines and used again in new electric machines. However, this is not a realistic option, as the magnets in current EVs were not designed to be removed and are often difficult to extract. The main goal of research in [117], [118], [119], [120], [121] 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 [122]. The last option is indirect recycling. Indirect recycling implies that the magnet scrap material is transformed into its elemental components. The RE elements are recovered from the magnets and separated from each other for use in subsequent PM production.

E. *Opportunities and Challenges*

As the transportation industry steers toward eco-conscious e-mobility, the realm of electric machine design is emerging with several intriguing research directions and challenges. This subsection discusses some key areas that present opportunities for advancement.

1) New materials:

- Iron nitride magnets (FeN) have garnered significant interest due to their unique properties and potential application in electric machines. This clean earth magnet can enable the mass production of high-performance PMs based entirely on abundant, sustainable input materials [123]. FeN PM has a high remanent flux density > 1.3 T at room temperature with a negative temperature coefficient, while the coercivity force is around –300 kA/m at room temperature with a positive temperature coefficient. In addition, the knee point is in the second quadrant [124].
- Nanocrystalline soft magnetic materials are characterized by extremely small grain sizes, typically only a few nanometers. These materials maintain their magnetic properties at elevated temperatures, ensuring reliable performance under demanding conditions and reducing the need for active cooling. The efficiency gains from using soft magnetic materials translate into significant energy savings over the lifetime of the electric machine [125]. However, soft magnetic alloys have not seen widespread adoption in electric machines, primarily due to challenges in large-scale manufacturing.

2) New electric machine topologies:

- The dual rotor homopolar AC machine (DHAM) is a novel electric machine with field excitation options of either a DC winding or RE-free PM, as shown in Fig. 15(a). The PM version achieves an extended constant power speed range without impacting the field intensity in the magnet, meeting the torque requirement of the vehicular market [126], [127].
- The bi-axial excitation synchronous machine (BESM) is another RE-free motor topology proposed for traction applications [128]. As the name bi-axial excitation implies, the rotor field is excited along both the d and q axes. This synchronous electric machine, with both ferrite magnets and field winding on the rotor shown in Fig. 15 (b), results in a torque density comparable to state-of-the-art EESMs in the literature.
- The experimental study in [129] shows that the 24/16 pole combination SRM is a promising technology that can respond to the increasing demand for high-performance and low-cost traction motors, presented in Fig. 15 (c). High torque ripple and acoustic noise that have been impeding the widespread use of SRM in propulsion applications are significantly reduced.
- The 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 [130], [131]. 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. WFFSM, shown in Fig. 15 (d), 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 stator type is relatively easy to manufacture with a high winding fill factor [130]. It also provides better cooling because windings are directly exposed to the stator housing with a cooling jacket. A double stator is another proposed WFFSM topology that elevates torque density and efficiency [132].
- In the RE-free permanent magnet-assisted synchronous reluctance machine (PMaSynRM), as illustrated in Fig. 15 (e), ferrite PMs are embedded in the rotor flux barriers to improve the performance of synchronous reluctance motor, addressing challenges like low power factor, low torque density, limited constant power speed range, and ohmic losses in the stator [133], [134]. Bi-magnet or hybrid-magnet (utilizing RE and ferrite PMs) SynRM is another approach to reduce the use of RE materials, as shown in Fig. 15 (f), [135], [136].
- PM-assisted wound-rotor synchronous machine (PM-assisted WRSM) represents a popular approach toward sustainability-centric electric machine design while enhancing torque performance and efficiency. Hybrid excited is the most used term in the literature to describe this type of electric machine [137].

3) New manufacturing

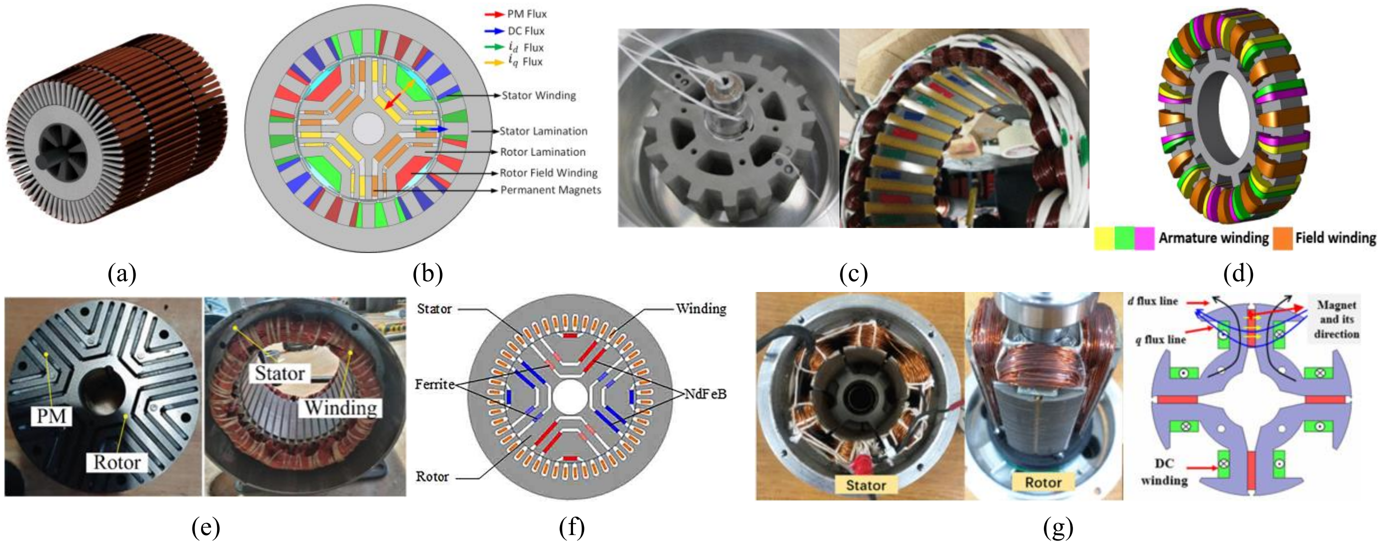


Fig. 15. (a) DHAM topology [111], (b) Bi-axial excitation synchronous machine [113], (c) 24/16 SRM [114], (d) Toroidal winding WFFSM [115], (e) PMaSynRM [118], (f) Bi-magnet SynRM [120], and (g) PM-assisted WRSM [122].

New technologies like additive manufacturing (AM), commonly known as 3D printing, provide unparalleled design freedom. It promises an era of unprecedented electric machine innovation, addressing the intricate interplay of magnetic, winding, and thermal dynamics [138], [139]. AM can optimize manufacturing processes, facilitate the creation of intricate designs, and ultimately enhance the overall performance, efficiency, and sustainability of electrical machines [140].

4) Industry 4.0 technologies

They are also referred to as smart manufacturing and have the potential to revolutionize electric machine production by incorporating circular economy principles, enhancing energy efficiency, and utilizing advanced technologies like smart sensors and digital twins. These innovations enable companies to create a data footprint through the sensors and monitoring of machines and equipment, integrating intelligent digital technologies into manufacturing and industrial processes [141], [142].

VI. Conclusions

This paper comprehensively reviews past, present, and future technologies for closing the circular economy loop 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.

Electric vehicle batteries and components containing critical raw materials are central to developing circular economy strategies. Multipurpose and reuse strategies aim to extend the life of these batteries, following a hierarchy to optimize life-cycle value through direct reuse, repurposing, refurbishment, and remanufacturing. Markets for battery disassembly and repacking for use in energy storage systems are already emerging.

For power electronic components, with a focus on waste printed circuit boards, this paper emphasizes the importance of circular economy practices. We discuss various methods for component extraction, metal recovery, and the use of innovative materials that enhance recyclability and sustainability. Advanced techniques, such as automation, AI, and machine vision, improve the precision and efficiency of component disassembly and sorting. By adopting these advanced recycling and reuse strategies, the industry can significantly reduce environmental impact, optimize resource recovery, and support sustainable manufacturing in power electronics. Transitioning to a circular economy can stimulate economic growth by creating new business opportunities and jobs in the repair, refurbishment, and recycling sectors.

Due to the high cost, limited availability, and environmental concerns of RE materials, it is imperative to explore alternative technologies to replace or reduce RE magnets in electrical machines. Highlighted are the advantages of energy savings, cost reduction, and environmental benefits associated with gathering and recycling materials in various electric machine topologies for propulsion system applications. The end-of-life stage of electric machines involves disassembly and shredding of the main components and materials. From a recycling perspective, designs that incorporate soft magnetic composites, segmented structures, environmentally friendly materials, and aluminum windings instead of copper are preferred. The use of electromagnet or ferrite PMs instead of NdFeB and minimizing glue application are also advantageous. Additionally, reducing material weight (and thus increasing torque density) is desirable, as it lowers the amount of material that ultimately requires recycling.

References

[1] T. Elwert *et al.*, “Current Developments and Challenges in the Recycling of Key Components of (Hybrid) Electric Vehicles,” *Recycling*, vol. 1, no. 1, pp. 25–60, Oct. 2015.

[2] M. Y. Metwly, M. S. Abdel-Majeed, A. S. Abdel-Khalik, R. A. Hamdy, M. S. Hamad and S. Ahmed, "A Review of Integrated On-Board EV Battery Chargers: Advanced Topologies, Recent Developments and

Optimal Selection of FSCW Slot/Pole Combination," in *IEEE Access*, vol. 8, pp. 85216-85242, 2020.
[3] T. Na, X. Yuan, J. Tang, and Q. Z. Hang, "A Review of on-Board Integrated Electric Vehicles Charger and a New Single-Phase Integrated Charger," *CPSS TPEA*, vol. 4, no. 4, Dec. 2019.
[4] S. Foti, A. Testa, G. Scelba, S. De Caro, and L. D. Tornello, "A V2G Integrated Battery Charger Based on an Open End Winding Multilevel Configuration," *IEEE Open J. Ind. Applicant.*, vol. 1, pp. 216–226, 2020.
[5] P. Pescetto, M. F. T. Cruz, F. Stella, and G. Pellegrino, "Galvanically Isolated On-Board Charger Fully Integrated With 6-Phase Traction Motor Drives," *IEEE Access*, vol. 11, pp. 26059–26069, 2023.
[6] S. Semsar, T. Soong, and P. W. Lehn, "On-Board Single-Phase Integrated Electric Vehicle Charger With V2G Functionality," *IEEE Trans Power Electron*, vol. 35, no. 11, pp. 12072–12084, Nov. 2020.
[7] Z. Wang *et al.*, "A Dual-Channel Magnetically Integrated EV Chargers Based on Double-Stator-Winding Permanent-Magnet Synchronous Machines," *IEEE Trans Ind Appl*, vol. 55, no. 2, pp. 1941–1953, Mar. 2019.
[8] C. Viana, M. Pathmanathan, and P. W. Lehn, "Dual-Inverter-Integrated Three-Phase EV Charger Based on Split-Phase Machine," *IEEE Trans Power Electron*, vol. 37, no. 12, pp. 15175–15185, Dec. 2022.
[9] V. Vidya and R. S. Kaarthik, "Parallel Operation of Integrated Battery Chargers for All Wheel Drive Electric Vehicles," in *IEEE Trans. on Transportation Electrification*, vol. 9, no. 2, pp. 3106-3114, June 2023.
[10] S. A. Singh, G. Carli, N. A. Azeez, and S. S. Williamson, "Modeling, Design, Control, and Implementation of a Modified Z-Source Integrated PV/Grid/EV DC Charger/Inverter," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 6, pp. 5213–5220, Jun. 2018.
[11] H. Wu, "A Survey of Battery Swapping Stations for Electric Vehicles: Operation Modes and Decision Scenarios," *IEEE Trans. Intell. Transport. Syst.*, vol. 23, no. 8, pp. 10163–10185, Aug. 2022.
[12] W. Infante, J. Ma, X. Han, and A. Liebman, "Optimal Recourse Strategy for Battery Swapping Stations Considering Electric Vehicle Uncertainty," *IEEE Trans. Intell. Transport. Syst.*, vol. 21, no. 4, pp. 1369–1379, Apr. 2020.
[13] X. Zhang, Y. Cao, L. Peng, N. Ahmad and L. Xu, "Towards Efficient Battery Swapping Service Operation Under Battery Heterogeneity," in *IEEE Transactions on Vehicular Technology*, vol. 69, no. 6, pp. 6107-6118, June 2020.
[14] L. Silvestri, M. De Santis, and G. Bella, "A Preliminary Techno-Economic and Environmental Performance Analysis of Using Second-Life EV Batteries in an Industrial Application," in *2022 6th Int. Conf. on Green Energy and Applications (ICGEA)*, Mar. 2022, pp. 99–102.
[15] C. McCrossan and K. Shankaravelu, "A Review of the Second Life Electric Vehicle Battery Landscape from a Business and Technology Perspective," in *2021 IEEE Green Technologies Conference (GreenTech)*, Apr. 2021, pp. 416–423.
[16] T. K. Agrawal, J. Angelis, J. R. Thakur, M. Wiktorsson, and R. Kalaiarasan, "Enabling circularity of electric vehicle batteries - the need for appropriate traceability," in *2021 IEEE Int. Conference on Technology Management, Operations and Decisions (ICTMOD)*, Nov. 2021, pp. 1–6.
[17] S. Maharajan, M. Jana, and S. Basu, "Handling of the End of Life Electric Vehicle Batteries for Stationary Storage Applications," in *2019 IEEE Transportation Electrification Conference (ITEC-India)*, Dec. 2019, pp. 1–5.
[18] P. Eleftheriadis *et al.*, "Second Life Batteries: Current Regulatory Framework, Evaluation Methods, and Economic Assessment: Reuse, refurbish, or recycle," *IEEE Ind. Appl. Mag.*, vol. 30, no. 1, pp. 46–58, Jan. 2024.
[19] C. Li, D. Xu, and G. Wang, "High efficiency remanufacturing of induction motors with interior permanent-magnet rotors and synchronous-reluctance rotors," in *2017 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)*, Aug. 2017, pp. 1–6.
[20] A. Kampker, A. Hollah, J. Triebs, and I. Aidi, "Remanufacturing of electric vehicles: Evaluation of economic potential," in *2019 IEEE 10th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT)*, Feb. 2019, pp. 122–127.
[21] R. Ni, L. Ding, X. Gui, G. Wang, G. Zhang, and D. Xu, "Remanufacturing of low-efficiency induction machines with interior permanent-magnet rotors for energy efficiency improvement," in *2014 17th International Conference on Electrical Machines and Systems (ICEMS)*, Oct. 2014, pp. 3161–3165.
[22] H. Chao, M. Xiuqin, and H. Hayashi, "Research on Used Electric and Electronic Equipment in China," in *2009 International Forum on Information Technology and Applications*, May 2009, pp. 221–224.
[23] "Electric vehicles from life cycle and circular economy perspectives - TERM 2018," *Europa.eu*, Nov. 22, 2018. https://www.eea.europa.eu/en/analysis/publications/electric-vehicles-from-life-cycle.
[24] A. Tripathy, A. Bhuyan, R. Padhy, and L. Corazza, "Technological, Organizational, and Environmental Factors Affecting the Adoption of Electric Vehicle Battery Recycling," *IEEE Trans Eng Manag*, vol. 71, pp. 12992–13005, 2024.
[25] M. Gupta, K. Ashok, V. Upadhyaya, and S. Nigam, "Metal Recovery from E-Waste by Recycling Techniques: A Review," *8th International Conference on Smart Structures and Systems, ICSSS 2022*, 2022, doi: 10.1109/ICSSS54381.2022.9782219.
[26] M. Peng, W. Layiding, X. Dong, G. Jiangang, and D. Guanghong, "A physical process for recycling and reusing waste printed circuit boards," in *IEEE International Symposium on Electronics and the Environment, 2004. Conference Record. 2004*, May 2004, pp. 237–242.
[27] H.-C. Zhang, X. Ouyang, and A. Abadi, "An Environmentally Benign Process Model Development for Printed Circuit Board Recycling," in *Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment, 2006.*, May 2006, pp. 212–217.
[28] J. Li, P. Shrivastava, Z. Gao, and H.-C. Zhang, "Printed circuit board recycling: a state-of-the-art survey," *IEEE Transactions on Electronics Packaging Manufacturing*, vol. 27, no. 1, pp. 33–42, Jan. 2004.
[29] K. Naito, A. Shirai, S. -i. Kaneko and G. Capi, "Recycling of printed circuit boards by robot manipulator: A Deep Learning Approach," *2021 IEEE International Symposium on Robotic and Sensors Environments (ROSE)*, FL, USA, 2021, pp. 1-5.
[30] M. Breier, W. Li, M. Bosling, T. Pretz, and D. Merhof, "Rotation estimation for printed circuit board recycling," in *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, Oct. 2014, pp. 3468–3474.
[31] W. Li, B. Esders, and M. Breier, "SMD segmentation for automated PCB recycling," in *2013 11th IEEE International Conference on Industrial Informatics (INDIN)*, Jul. 2013, pp. 65–70.
[32] Q. Niu, D. Xiang, X. Liu, G. Duan, and C. Shi, "The Recycle Model of Printed Circuit Board and Its Economy Evaluation," in *Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment*, May 2007, pp. 106–111.
[33] M. Szymanski, B. Michalski, M. Leonowicz, and Z. Miazga, "Application of the HDDR method for recycling of Nd-Fe-B magnets," in *2015 IEEE International Magnetics Conference (INTERMAG)*, May 2015, p. 1.
[34] R. Hernandez-Millan, J. R. Pacheco-Pimentel, and J. Salinas, "Design principles for recycling induction motors," in *IEMDC 2001. IEEE International Electric Machines and Drives Conference (Cat. No.01EX485)*, Jun. 2001, pp. 782–788.
[35] D. Joklitschke, U. Pflanz, R. Stein, D. Goll, and G. Schneider, "Direct recycling of high coercivity Fe-Nd-B based sintered magnets by doping with Nd-rich alloy," in *2017 IEEE International Magnetics Conference (INTERMAG)*, Apr. 2017, pp. 1–2.
[36] S. Ghorbanighoshchi, D. Celebi, N. G. Akdogan, and O. Akdogan, "Recycling and Enrichment of Rare Earth Based Permanent Magnet Scraps," in *2023 IEEE International Magnetic Conference (INTERMAG)*, May 2023, pp. 1–4.
[37] B. Karlsson, J. O. Jarrhed, and P. Wide, "Vision feature fusion for classification of electrical motors in an industrial recycling process," in *Proceedings. 1999 IEEE/SICE/RSJ. International Conference on Multisensor Fusion and Integration for Intelligent Systems. MFI'99,* Aug. 1999, pp. 87–92.
[38] A. K. Jha *et al.*, "Weighted Index of Recycling and Energy (WIRE) Cost for Motors in Electric Vehicles," in *2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, Jun. 2018, pp. 407–412.
[39] X. Zhang, D. Gerada, Z. Xu, F. Zhang, and C. Gerada, "A Review of Carbon Emissions from Electrical Machine Materials," *Electronics (Basel)*, vol. 13, no. 9, p. 1714, Jan. 2024.
[40] L. C. Casals, B. Amante García, and C. Canal, "Second life batteries lifespan: Rest of useful life and environmental analysis," *J Environ Manage*, vol. 232, pp. 354–363, Feb. 2019.
[41] S. Glöser-Chahoud *et al.*, "Industrial disassembling as a key enabler of circular economy solutions for obsolete electric vehicle battery systems," *Resour Conserv Recycl*, vol. 174, Nov. 2021.

[42] S. Jaman, S. Chakraborty, D. D. Tran, T. Geury, M. El Baghdadi, and O. Hegazy, "Review on Integrated On-Board Charger-Traction Systems: V2G Topologies, Control Approaches, Standards and Power Density State-of-the-Art for Electric Vehicle," *Energies 2022, Vol. 15, Page 5376*, vol. 15, no. 15, Jul. 2022.
[43] B. E. Lebrouhi, Y. Khattari, B. Lamrani, M. Maaroufi, Y. Zeraouli, and T. Kousksou, "Key challenges for a large-scale development of battery electric vehicles: A comprehensive review," *J Energy Storage*, vol. 44, p. 103273, Dec. 2021.
[44] A. M. Vallera, P. M. Nunes, and M. C. Brito, "Why we need battery swapping technology," *Energy Policy*, vol. 157, p. 112481, Oct. 2021.
[45] "Developing a Multipurpose Battery Swapping Station to Energize Mobile and Stationary Loads Energy Proceedings." [Online]. Available: https://www.energy-proceedings.org/developing-a-multipurpose-battery-swapping-station-to-energize-mobile-and-stationary-loads/
[46] "Criticality and recycling of lithium-ion batteries - Putting the debate on a broader footing." Accessed: Dec. 31, 2024. [Online]. Available: https://www.researchgate.net/publication/363096112.
[47] C. H. Illa Font *et al.*, "Second Life of Lithium-Ion Batteries of Electric Vehicles: A Short Review and Perspectives," *Energies 2023, Vol. 16, Page 953*, vol. 16, no. 2, p. 953, Jan. 2023.
[48] "Second life battery capacity - globally 2030." [Online]. Available: https://www.statista.com/statistics/876624/global-second-life-battery-capacity/.
[49] "Second-life EV Batteries Add Capacity to Solar Storage Facility - News." [Online]. Available: https://eepower.com/news/second-life-ev-batteries-add-capacity-to-solar-storage-facility/
[50] D. Holger and G. Petroni, "Old Electric-Vehicle Batteries Are Getting a Second Life," *Wall Street Journal*, Jun. 2022, [Online]. Available: https://www.wsj.com/articles/old-electric-vehicle-batteries-are-getting-a-second-life-11655114401.
[51] A. Alamalhodaei, "Lucid Motors sees a second life for its EV batteries in energy storage," Mar. 2021. [Online]. Available: https://techcrunch.com/2021/03/17/lucid-motors-sees-a-second-life-for-its-ev-batteries-in-energy-storage/.
[52] C. Murray, "Second life energy storage firms position themselves ahead of EV battery boom," Jan. 2023. [Online]. Available: https://www.energy-storage.news/second-life-energy-storage-firms-position-themselves-ahead-of-ev-battery-boom/.
[53] B. Editors, "Opportunities and Challenges of Second-Life Batteries," Feb. 2024. [Online]. Available: https://medium.com/batterybits/opportunities-and-challenges-of-second-life-batteries.
[54] X. Gu *et al.*, "Challenges and opportunities for second-life batteries: Key technologies and economy," *Renewable and Sustainable Energy Reviews*, vol. 192, p. 114191, Mar. 2024.
[55] M. F. Börner *et al.*, "Challenges of second-life concepts for retired electric vehicle batteries," *Cell Rep Phys Sci*, vol. 3, no. 10, p. 101095, Oct. 2022.
[56] A. Sangwongwanich, D.-I. Stroe, C. Mi, and F. Blaabjerg, "Sustainability of Power Electronics and Batteries: A Circular Economy Approach," *IEEE Power Electronics Magazine*, vol. 11, no. 1, pp. 39–46, Mar. 2024.
[57] "World Economic Forum." Accessed: Dec. 31, 2024. [Online]. Available: https://www.weforum.org/publications/a-new-circular-vision-for-electronics-time-for-a-global-reboot/.
[58] "Battery Recycling | Cleantech Group." Accessed: Dec. 31, 2024. [Online]. Available: https://www.cleantech.com/battery-recycling/.
[59] "How Are EV Batteries (Actually) Recycled?," Oct. 2023. [Online]. Available: https://blog.ucsusa.org/jessica-dunn/how-are-ev-batteries-actually-recycled/.
[60] "How well can electric vehicle batteries be recycled? | MIT Climate Portal." Accessed: Dec. 31, 2024. [Online]. Available: https://climate.mit.edu/ask-mit/how-well-can-electric-vehicle-batteries-be-recycled.
[61] M. Dusseldorp, A. Fox, S. Glöser, and S. Heinz, *Criticality and recycling of lithium-ion batteries - Putting the debate on a broader footing*. 2022.
[62] L. Gaines, Q. Dai, J. T. Vaughey, and S. Gillard, "Direct Recycling R\&{D} at the ReCell Center," *Recycling*, vol. 6, no. 2, p. 31, Jun. 2021.
[63] C. Wu, A. K. Awasthi, W. Qin, W. Liu, and C. Yang, "Recycling value materials from waste PCBs focus on electronic components: Technologies, obstruction and prospects," *J Environ Chem Eng*, vol. 10, no. 5, p. 108516, Oct. 2022.
[64] Y. Lu and Z. Xu, "Precious metals recovery from waste printed circuit boards: A review for current status and perspective," *Resour Conserv Recycl*, vol. 113, pp. 28–39, Oct. 2016.
[65] E. A. Oke and H. Potgieter, "Discarded e-waste/printed circuit boards: a review of their recent methods of disassembly, sorting and environmental implications," *J Mater Cycles Waste Manag*, vol. 26, no. 3, pp. 1277–1293, May 2024.
[66] Z. Chen, M. Yang, Q. Shi, X. Kuang, H. J. Qi, and T. Wang, "Recycling Waste Circuit Board Efficiently and Environmentally Friendly through Small-Molecule Assisted Dissolution," *Sci Rep*, vol. 9, no. 1, p. 17902, Nov. 2019.
[67] "How to recycle waste PCBs Latest Articles News," Sep. 2022. [Online]. Available: https://electronics-sourcing.com/2022/09/06/how-to-recycle-waste-pcbs/.
[68] W. Zhao, J. Xu, W. Fei, Z. Liu, W. He, and G. Li, "The reuse of electronic components from waste printed circuit boards: a critical review," *Environmental Science Advances*, vol. 2, no. 2, pp. 196–214, Feb. 2023.
[69] H. Li, J. Eksteen, and E. Oraby, "Hydrometallurgical recovery of metals from waste printed circuit boards (WPCBs): Current status and perspectives – A review," *Resour Conserv Recycl*, vol. 139, pp. 122–139, Dec. 2018.
[70] "Global Top 10 Lithium-ion Battery Recycling Companies [2024]." Accessed: Dec. 31, 2024. [Online]. Available: https://www.blackridgeresearch.com/blog/list-of-top-global-lithium-ion-li-ion-electric-vehicle-ev-battery-lib-closed-loop-recycling-services-companies-in-the-world.
[71] "The technology overview: closing the lithium supply gap with direct lithium extraction (DLE) and battery recycling | by Max Werny | Extantia Capital | Medium." Accessed: Dec. 31, 2024. [Online]. Available: https://medium.com/extantia-capital/the-technology-overview-closing-the-lithium-supply-gap-with-direct-lithium-extraction-dle-and-d686e0e7a923.
[72] "Direct Recycling of Materials - ReCell Center." Accessed: Dec. 31, 2024. [Online]. Available: https://recellcenter.org/research/direct-recycling-of-materials/.
[73] "Almost 100%-recyclable circuit board turns to jelly for disassembly," Apr. 2024. [Online]. Available: https://newatlas.com/materials/vitrimer-recyclable-printed-circuit-board/
[74] Z. Zhang *et al.*, "Recyclable vitrimer-based printed circuit boards for sustainable electronics," *Nat Sustain*, vol. 7, no. 5, pp. 616–627, May 2024.
[75] M. Marconi, G. Palmieri, M. Callegari, and M. Germani, "Feasibility Study and Design of an Automatic System for Electronic Components Disassembly," *J Manuf Sci Eng*, vol. 141, no. 021011, Dec. 2018.
[76] "Recovering Critical Raw Materials from WEEE using Artificial Intelligence," 2022.
[77] A. Di Gerlando *et al.*, "Circularity potential of electric motors in e-mobility: methods, technologies, challenges," *Journal of Remanufacturing 2024 14:2*, vol. 14, no. 2, pp. 315–357, Dec. 2024.
[78] T. Elwert, D. Goldmann, F. Roemer, and S. Schwarz, "Recycling of NdFeB Magnets from Electric Drive Motors of (Hybrid) Electric Vehicles," *Journal of Sustainable Metallurgy*, vol. 3, no. 1, pp. 108–121, Mar. 2017.
[79] I. C. Nlebedim and A. H. King, "Addressing Criticality in Rare Earth Elements via Permanent Magnets Recycling," *JOM*, vol. 70, no. 2, pp. 115–123, Feb. 2018.
[80] M. Fereydoonian and W. Lee, "Closing the Loop on Circular Economy in Transportation Electrification: Reuse, Repurposing, and Recycling of Power Electronics and Electric Machines," *2024 IEEE Transportation Electrification Conference and Expo, ITEC 2024*, 2024.
[81] J. R. Pérez-Cardona, J. W. Sutherland, and S. D. Sudhoff, "Optimization-Based Design Model for Electric Traction Motors Considering the Supply Risk of Critical Materials," *IEEE Open Access Journal of Power and Energy*, vol. 10, pp. 316–326, 2023.
[82] E. Westberg, M. Gustafsson, and N. Svensson, "Environmental Impact of an Electric Motor and Drive-Life Cycle Assessment and a study of a Circular Business Model Author", Accessed: Dec. 31, 2024. [Online]. Available: www.liu.
[83] R. Barkhausen, A. Durand, Y. Y. Fong, V. Zeller, and C. Rohde, "Modeling stock, material and environmental impacts of circular economy product policies. Trade-offs between early replacement and repair of electric motors," *Resour Conserv Recycl*, vol. 205, p. 107600, Jun. 2024.
[84] X. Zhang, Z. Xu, C. Gerada, and D. Gerada, "Carbon Emission Analysis of Electrical Machines," *ICEMS 2021 - 2021 24th International Conference on Electrical Machines and Systems*, pp. 1678–1683, 2021.

[85] J. Abdollahi *et al.*, "Environmental impact assessment of aluminium production using the life cycle assessment tool and multi-criteria analysis," *Annals of Environmental Science and Toxicology*, vol. 5, no. 1, pp. 59–66, Jun. 2021.
[86] A. Acquaviva, M. DIana, B. Raghuraman, L. Petersson, and S. Nategh, "Sustainability Aspects of Electrical Machines for E-Mobility Applications Part II: Aluminium Hairpin vs. Copper Hairpin," *IECON Proceedings (Industrial Electronics Conference)*, vol. 2021-October, Oct. 2021.
[87] B. Raghuraman, S. Nategh, N. Sidiropoulos, L. Petersson, and A. Boglietti, "Sustainability Aspects of Electrical Machines for E-Mobility Applications Part I: A Design with Reduced Rare-earth Elements," *IECON Proceedings (Industrial Electronics Conference)*, vol. 2021-October, Oct. 2021.
[88] "TRADING ECONOMICS 20 million INDICATORS FROM 196 COUNTRIES." [Online]. Available: https://tradingeconomics.com/
[89] "Copper - Price - Chart - Historical Data - News." Accessed: Dec. 31, 2024. [Online]. Available: https://tradingeconomics.com/commodity/copper.
[90] "OnlineMetals.com® | Online Metal Supply | Buy Raw Materials Online from OnlineMetals.com." Accessed: Dec. 31, 2024. [Online]. Available: https://www.onlinemetals.com/.
[91] "Copper PRICE Today | Copper Spot Price Chart | Live Price of Copper per Ounce | Markets Insider." Accessed: Dec. 31, 2024. [Online]. Available: https://markets.businessinsider.com/commodities/copper-price.
[92] "Understand your copper emissions." Accessed: Dec. 31, 2024. [Online]. Available: https://www.carbonchain.com/blog/understand-your-copper-emissions
[93] "Embodied Carbon: Key Considerations for Key Materials." Accessed: Dec. 31, 2024. [Online]. Available: https://www.canadianarchitect.com/embodied-carbon-keyconsiderations-for-key-materials/.
[94] "Environmental Priority Strategies (EPS)." [Online]. Available: https://www.ivl.se/english/ivl/our-offer/our-focus-areas/consumption-and-production/environmental-priority-strategies-eps.
[95] "Reduced rare earth and magnet-free motors," Apr. 2023. [Online]. Available: https://www.emobility-engineering.com/reduced-rare-earth-and-magnet-free-motors/.
[96] "BMW Reveals Revolutionary Tech In Its Fifth Generation Electric Motor," Jan. 2022. [Online]. Available: https://www.motortrend.com/news/bmw-ix-m60-brushed-electric-motor-tech-deep-dive/.
[97] "ZF makes magnet-free electric motor uniquely compact and competitive." [Online]. Available: https://press.zf.com/press/en/releases/release_60480.
[98] "MAHLE develops highly efficient magnet-free electric motor - MAHLE Newsroom." [Online]. Available: https://newsroom.mahle.com/press/en/press-releases/mahle-develops-highly-efficient-magnet-free-electric-motor–82368#
[99] B. Fahimi *et al.*, "Automotive Electric Propulsion Systems: A Technology Outlook," *IEEE Transactions on Transportation Electrification*, vol. 10, no. 3, pp. 5190–5214, Sep. 2024, doi: 10.1109/TTE.2023.3321707.
[100] B. Burkhart, A. Klein-Hessling, I. Ralev, C. P. Weiss, and R. W. De Doncker, "Technology, research and applications of switched reluctance drives," *CPSS Transactions on Power Electronics and Applications*, vol. 2, no. 1, pp. 12–27, 2017.
[101] W. Uddin, T. Husain, Y. Sozer, and I. Husain, "Design Methodology of a Switched Reluctance Machine for Off-Road Vehicle Applications," *IEEE Trans Ind Appl*, vol. 52, no. 3, pp. 2138–2147, May 2016.
[102] S. Mafrici, V. Madonna, C. Maria Meano, K. Friis Hansen, and A. Tenconi, "Switched Reluctance Machine for Transportation and Eco-Design: A Life Cycle Assessment," *IEEE Access*, vol. 12, pp. 68334–68344, 2024.
[103] M. Popescu, J. Goss, D. A. Staton, D. Hawkins, Y. C. Chong, and A. Boglietti, "Electrical Vehicles - Practical Solutions for Power Traction Motor Systems," *IEEE Trans Ind Appl*, vol. 54, no. 3, pp. 2751–2762, May 2018.
[104] Z. Q. Zhu and D. Howe, "Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 746–765, Apr. 2007.
[105] R. Thomas, L. Garbuio, L. Gerbaud, and H. Chazal, "Modeling and design analysis of the Tesla Model S induction motor," in *2020 International Conference on Electrical Machines (ICEM)*, Aug. 2020, pp. 495–501.
[106] Z. Yang, F. Shang, I. P. Brown, and M. Krishnamurthy, "Comparative Study of Interior Permanent Magnet, Induction, and Switched Reluctance Motor Drives for EV and HEV Applications," *IEEE Transactions on Transportation Electrification*, vol. 1, no. 3, pp. 245–254, Oct. 2015.
[107] "Service and diagnostic information for independent businesses and individuals involved in the professional maintenance and repair of Tesla vehicles." [Online]. Available: https://service.tesla.com/vehicle-models/roadster.
[108] P. Ramesh and N. C. Lenin, "High Power Density Electrical Machines for Electric Vehicles—Comprehensive Review Based on Material Technology," *IEEE Trans Magn*, vol. 55, no. 11, pp. 1–21, Nov. 2019.
[109] "Performance Analysis of the Tesla Model 3 Electric Motor using MotorXP-PM," 2020, Accessed: Dec. 31, 2024. [Online]. Available: http://motorxp.com.
[110] "Mercedes-Benz EQC Battery, Powertrain & Range Explained: Video." Accessed: Dec. 31, 2024. [Online]. Available: https://insideevs.com/news/339461/mercedes-benz-eqc-battery-powertrain-range-explained-video/.
[111] "Audi e-tron electric motors & setup :: electrichasgoneaudi.net." [Online]. Available: https://electrichasgoneaudi.net/models/e-tron/drivetrain/motor/.
[112] Admin, "How does the Renault ZOE motor work?," Mar. 2021. [Online]. Available: https://back.renaultgroup.com/magazine/energies-et-motorisation/le-moteur-de-renault-zoe-puissance-et-efficacite-energetique/.
[113] "Mystery of the Tesla's Next-Gen Zero-Rare-Earth Electric Motor." [Online]. Available: https://motorxp.com/tesla-model3-motor-redesigned-axial-ferrite/.
[114] "SKF." [Online]. Available: https://www.skf.com/us/news-and-events/news/2019/2019-05-17-customised-and-hybrid-bearings-solve-fundamental-issues-in-electric-vehicles.
[115] "Copper Alliance InSite." [Online]. Available: https://insite.copperalliance.org/.
[116] C. A. Stockton, R. F. McElveen, and E. Chastain, "The Integral Role of Electric Motors in Achieving Sustainability," *IEEE Trans Ind Appl*, vol. 60, no. 5, pp. 7949–7957, Sep. 2024.
[117] lucian, "https://symposium.etn-demeter.eu/." [Online]. Available: https://symposium.etn-demeter.eu/.
[118] A. G. Gonzalez, D. Wang, J.-M. Dubus, and P. O. Rasmussen, "Design and Experimental Investigation of a Hybrid Rotor Permanent Magnet Modular Machine with 3D Flux Paths Accounting for Recyclability of Permanent Magnet Material," *Energies (Basel)*, vol. 13, no. 6, p. 1342, Jan. 2020.
[119] M. Alatalo, S. T. Lundmark, and E. A. Grunditz, "Electric machine design for traction applications considering recycling aspects-review and new solution," in *IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society*, Nov. 2011, pp. 1836–1841.
[120] T. Vaimann, A. Kallaste, A. Kilk, and A. Belahcen, "Lifecycle-based design and optimization of electrical motor-drives - Challenges and possibilities," in *2013 3rd International Conference on Electric Power and Energy Conversion Systems*, Oct. 2013, pp. 1–4.
[121] V. Debusschere, B. Multon, H. B. Ahmed, P. E. Cavarec and P. Geriniere, "Minimization of life cycle energy cost of a single-phase induction motor," *2009 IEEE International Electric Machines and Drives Conference*, Miami, FL, USA, 2009, pp. 1441-1448.
[122] "Project – European Training Network for the Design and Recycling of Rare-Earth Permanent Magnet Motors and Generators in Hybrid and Full Electric Vehicles (DEMETER)." Accessed: Dec. 31, 2024. [Online]. Available: https://etn-demeter.eu/project/.
[123] "Home." [Online]. Available: https://www.nironmagnetics.com/.
[124] A. Al-Qarni and A. El-Refaie, "Optimum Rotor Design for Rare-Earth Free High Performance Traction Applications Interior Permanent Magnet Motors Enabled by Iron Nitride Permanent Magnet," in *2023 IEEE International Electric Machines & Drives Conference (IEMDC)*, May 2023, pp. 1–7.
[125] samkernion, "CorePower Magnetics Publishes White Paper on Next-Generation Electric Motor Technology," Oct. 2024. [Online]. Available: https://www.corepowermagnetics.com/post/corepower-magnetics-publishes-white-paper-on-next-generation-electric-motor-technology.
[126] T. Ruekamnuaychok *et al.*, "A Novel Dual-Rotor Homopolar AC Machine," *IEEE Open Access Journal of Power and Energy*, vol. 11, pp. 546–557, 2024.

[127] S. Sudhoff, J. Zhong, and S. Pekarek, "Dual rotor homopolar ac machine," May 2022. [Online]. Available: https://patents.google.com/patent/US20220140712A1/en.

[128] R. Chattopadhyay, J. Jung, Md. S. Islam, I. Boldea, and I. Husain, "Rare-Earth Free Unity Power Factor Bi-Axial Excitation Synchronous Machine for Traction Applications," *IEEE Trans Ind Appl*, vol. 60, no. 4, pp. 5966–5978, Jul. 2024.

[129] B. Bilgin *et al.*, "Making the Case for Switched Reluctance Motors for Propulsion Applications," *IEEE Trans Veh Technol*, vol. 69, no. 7, pp. 7172–7186, Jul. 2020.

[130] M. Fereydoonian, K. Lee, G. Choi, and W. Lee, "Rotor Saliency Optimization for High-Power Density Wound-Field Flux-Switching Machines," in *2023 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct. 2023, pp. 3867–3874.

[131] M. Fereydoonian, D. Bobba, and W. Lee, "Multi-Segment Magnetic Flux Path Analysis of Wound-Field Flux-Switching Machines with Different Winding and Stator-Rotor Combinations," *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, pp. 1–11, 2024.

[132] U. B. Akuru, W. Ullah, D. E. Okojie, L. Masisi, H. C. Idoko, and F. Khan, "Comparative Performance Evaluation, Prototyping and Experimentation of the Double-Stator Wound-Field Flux Switching Machine," *IEEE Trans Ind Appl*, vol. 60, no. 5, pp. 6706–6714, Sep. 2024.

[133] G. Xu, Z. Jia, Q. Chen, J. Xia, Y. Cai, and Z. Zhang, "A Fast and Effective Optimization Procedure for the Ferrite PMaSynRM to Reduce Material Cost," *IEEE Transactions on Transportation Electrification*, vol. 10, no. 1, pp. 635–647, Mar. 2024.

[134] M. Al-ani, A. Walker, G. Vakil, D. Gerada, C. Gerada, and K. Paciura, "Modifications to PM-Assisted Synchronous Reluctance Machine to Achieve Rare-Earth Free Heavy-Duty Traction," *IEEE J Emerg Sel Top Power Electron*, vol. 11, no. 2, pp. 2029–2038, Apr. 2023.

[135] Y. Xie, J. Shao, S. He, B. Ye, F. Yang, and L. Wang, "Novel PM-Assisted Synchronous Reluctance Machines Using Asymmetrical Rotor Configuration," *IEEE Access*, vol. 10, pp. 79564–79573, 2022.

[136] Z. S. Du and T. A. Lipo, "Cost-Effective High Torque Density Bi-Magnet Machines Utilizing Rare Earth and Ferrite Permanent Magnets," *IEEE Transactions on Energy Conversion*, vol. 35, no. 3, pp. 1577–1584, Sep. 2020.

[137] W. Chai, H.-M. Yang, F. Xing, and B. Kwon, "Analysis and Design of a PM-Assisted Wound Rotor Synchronous Machine With Reluctance Torque Enhancement," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 4, pp. 2887–2897, Apr. 2021.

[138] L. Gargalis *et al.*, "Additive Manufacturing and Testing of a Soft Magnetic Rotor for a Switched Reluctance Motor," *IEEE Access*, vol. 8, pp. 206982–206991, 2020.

[139] T. Chowdhury *et al.*, "Thermal Management System for an Electric Machine With Additively Manufactured Hollow Conductors With Integrated Heat Pipes," *IEEE Trans Ind Appl*, vol. 60, no. 3, pp. 3763–3772, May 2024.

[140] A. Selema, M. N. Ibrahim, and P. Sergeant, "Advanced Manufacturability of Electrical Machine Architecture through 3D Printing Technology," *Machines*, vol. 11, no. 9, p. 900, Sep. 2023.

[141] D. Tiwari, J. Miscandlon, A. Tiwari, and G. W. Jewell, "A Review of Circular Economy Research for Electric Motors and the Role of Industry 4.0 Technologies," *Sustainability*, vol. 13, no. 17, p. 9668, Jan. 2021.

[142] A. Mayr *et al.*, "Electric Motor Production 4.0 – Application Potentials of Industry 4.0 Technologies in the Manufacturing of Electric Motors," in *2018 8th International Electric Drives Production Conference (EDPC)*, Dec. 2018, pp. 1–13.