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Review

A Survey on the Sustainability of Traditional and Emerging Materials for Next-Generation EV Motors

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Abstract: The transportation sector is experiencing a profound shift, driven by the urgent need to reduce greenhouse gas (GHG) emissions from internal combustion engine vehicles (ICEVs). As electric vehicle (EV) adoption accelerates, the sustainability of the materials used in their production, particularly in electric motors, is becoming a critical focus. This paper examines the sustainability of both traditional and emerging materials used in EV traction motors, with an emphasis on permanent magnet synchronous motors (PMSMs), which remain the dominant technology in the industry. Key challenges include the environmental and supply-chain concerns associated with rare earth elements (REEs) used in permanent magnets, as well as the sustainability of copper windings. Automakers are exploring alternatives such as REE-free permanent magnets, soft magnetic composites (SMCs) for reduced losses in the core, and carbon nanotube (CNT) windings for superior electrical, thermal, and mechanical properties. The topic of materials for EV traction motors is discussed in the literature; however, the focus on environmental, social, and economic sustainability is often lacking. This paper fills the gap by connecting the technological aspects with sustainability considerations, offering insights into the future configuration of EV motors.

Keywords: sustainability; electric vehicles; electric motor; permanent magnets; rare-earth elements; winding; copper; soft magnetic material; carbon nanotube conductors

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1. Introduction

The transportation sector is undergoing a significant transformation. Increasing environmental concerns about greenhouse gas (GHG) emissions and pollutants produced by conventional internal combustion engine vehicles (ICEVs) have led to a gradual decline in the sales of ICEVs. This shift is closely tied to the global effort to reduce reliance on fossil fuels and achieve net-zero greenhouse gas emissions by 2050, as outlined in the 2015 Paris 21st Conference of Parties (COP21) agreement on climate change mitigation. According to the International Energy Agency (IEA), 14 million electric vehicles (EVs), including battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs), were sold worldwide in 2023, corresponding to nearly 20% of the total marker [1].

It is well-recognized that EVs have several advantages in terms of maintenance services [2], and with the increasing battery lifetime and deployment of charging infrastructures, significant growth is projected in the production and sales of EVs in the coming years, as illustrated in Figure 1. In 2019, 7.2 million electric cars were sold globally. Based on current projections, annual electric vehicle sales are expected to reach 9 million units by 2025 and nearly 26 million by 2030. Additionally, it is anticipated that global annual sales of electric cars will surpass those of internal combustion engine vehicles before 2040 [3].

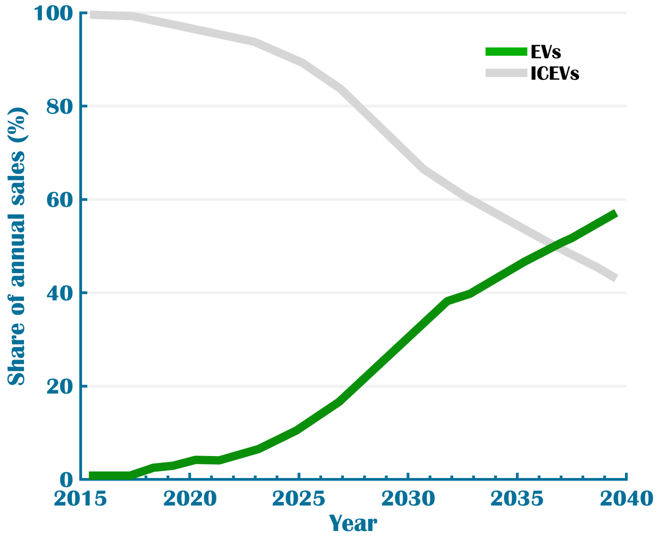


Figure 1. Forecasting global electric car sales over the next 20 years. Reproduced from BloombergNEF's Electric Vehicle Outlook 2019 [4].

In 2022, the IEA reported 34 billion tonnes of CO_2 emissions from fuel combustion [5], 24% of which (approximately 8 billion tonnes) are due to the transport sector [6]. Moreover, it is recognized that private cars and vans are responsible for around 10% of global CO_2 emissions [7]. Emissions from transportation are also increasing faster than those from any other sector, making it critical to implement effective measures to address this rising trend.

The electrification of transport systems is a crucial step in reducing global emissions, with electric vehicles set to play a pivotal role in decarbonization and lowering air pollution levels. Many researchers use the Life Cycle Assessment (LCA) to compare the environmental impact of EVs with that of traditional ICEVs [8,9].

As pointed out in [10], three legs for the sustainability of EVs are highlighted: (i) fabrication stage, (ii) lifetime usage, and (iii) disposal and end-of-life (EoL) recycling process. The literature reports contradictory results in terms of GHG emissions between EVs and conventional ICEVs [11], however, as illustrated in Figure 2, it is recognized that EVs have higher CO_2 emissions in the production stage and lower CO_2 emissions in the usage phase [12,13]. The former is mainly due to the high energy consumption and GHG emissions associated with preparing the battery pack [12,14]. The reduction in battery pack costs, currently driven by lithium-ion (Li-ion) technology, along with improvements in capacity, represents the key technological challenge for the widespread adoption of EVs. The latter is strictly affected by the type of fuel used in the generation of electric energy.

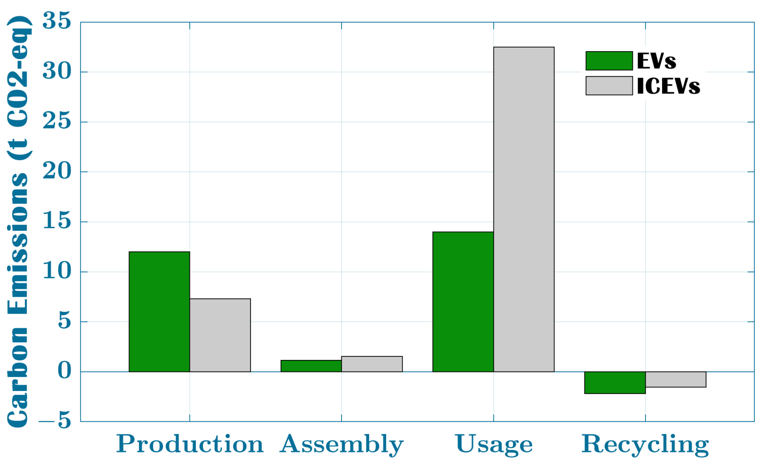


Figure 2. Comparative life-cycle CO_2 emissions for EVs and ICEVs. Reproduced from [13].

The sustainability of electrification of the transport sector must concern not only the economic, technical, and environmental perspectives but also the political and social sphere [15–17].

While most public and scientific attention on EV advancements is currently centered on battery technology, the electric traction motor is the true core of the energy conversion process. Extensive research explores the current challenges and emerging trends in electric motor development, and how these factors influence the electrification of the transportation sector [18–21]. Research typically focuses on the sustainability challenges and emerging materials associated with permanent magnet synchronous motors (PMSMs), as they are the preferred choice for EV manufacturers [18,22]. However, an electric motor consists of many components, each of which is crucial to the development of next-generation EV motors and is a key focus of ongoing research. With these considerations in mind, this research addresses the question: "What will the future configuration of EV motors look like"? This paper examines both traditional and emerging materials to chart a potential path for the evolution of EV motors, with a particular focus on the materials used for:

- Permanent magnets (PMs),
- Ferromagnetic core,
- Windings.

It is worth mentioning that the topic of materials for EV traction motors is widely discussed in the literature [22–25]. However, the focus on environmental, social, and economic sustainability is often lacking. This paper fills the gap by connecting the technological aspects with sustainability considerations.

The paper is organized as follows. A general overview of the EV market and EV traction motors is given in Section 2. Section 3 discusses the traditional materials for EV traction motors, while emerging materials for permanent magnets, ferromagnetic cores, and windings are analyzed in Section 4. In conclusion, Section 5 wraps up the paper by highlighting the main findings and suggesting directions for future research and investigation.

2. Current Status of EV Traction Motors

In this section, a summary of the current status of EV traction motor topologies is given. Different topologies of traction motors have been investigated and performances compared [26–29]. Generally, three classes of EV traction motors are currently considered: (i) PMSMs, (ii) switched reluctance motors (SRMs), and (iii) induction motors (IMs), each characterized by pros and cons [29–32]. As pointed out in [33], the following characteristics are required for an EV traction motor:

- High torque density,
- High overload capability,
- Low torque ripple,
- Large flux-weakening capability,
- High efficiency to reduce the losses,

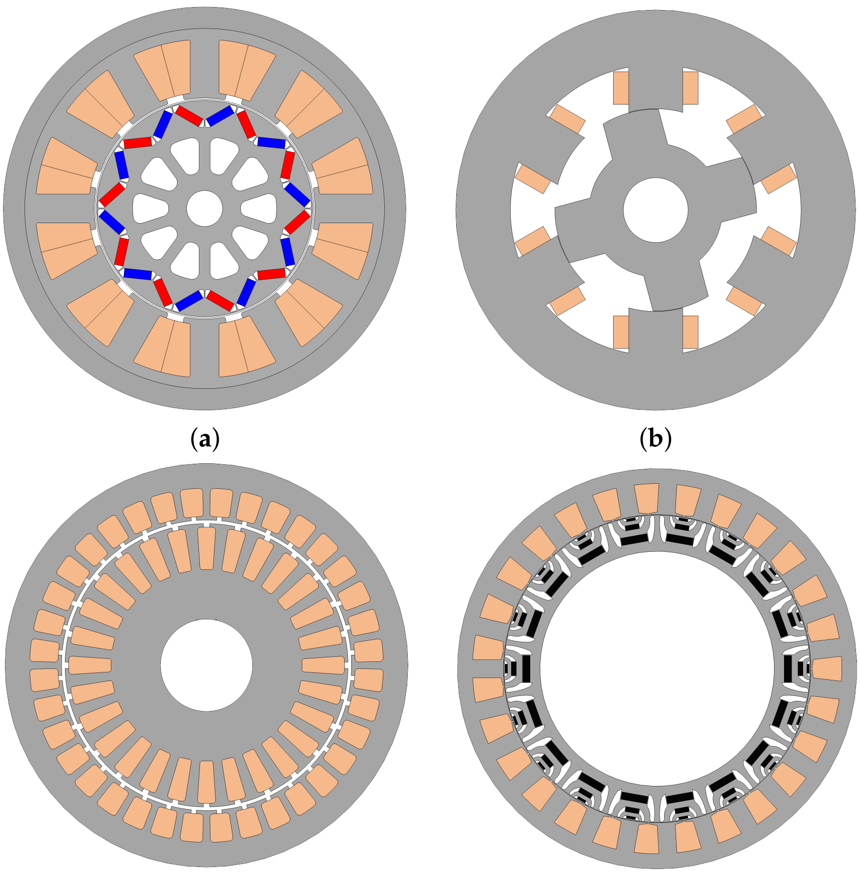
A list of motor types for some BEVs, including the production year, is given in Table 1. Most EVs, approximately 90% of the total, are equipped with a PMSM, as is confirmed by the market trend [34].

PM-free traction motors, such as the IM and the synchronous reluctance motor (SynRM), are not widely adopted within the current EV industry due to technical limitations; however, they continue to attract significant interest [35,36]. IM, as an alternative to PMSM, offers the key advantage of allowing the excitation field to be switched off, eliminating iron losses when the motor is not in operation.

SynRMs exhibit reduced torque density and power factor if compared to interior permanent magnet (IPM) motors. However, the performance of SynRM can be increased by inserting PMs [18,37]. In literature, this machine is called permanent magnet-assisted SynRM (PMaSynRM). Looking at Table 1, it can be noticed that Tesla EVs are equipped with such kind of traction motors. Schematic representations of the cross-sections of PMSM, SRM, IM, and PMaSynRM are shown in Figure 3. Another PM-free motor is the externally excited synchronous motor (EESM), installed in Renault Zoe and BMW ix3 vehicles [38,39], characterized by a higher value of power density if compared to IMs. Recently, a rotating transformer with a wireless power transmission system has been proposed to improve the transmission of energy to the rotor [40].

Table 1. List of BEVs, including production year and motor type [39,41–43].

EV Model	Motor Type	Year	Power [kW]
Audi Q6 e-tron	IM (front) + PMSM (rear)	2024	285
BMW i5 Touring	EESM	2024	250
Chevrolet Equinox EV	PMSM	2024	159–215
Hyundai Ioniq 5	PMSM	2021	125
Honda e:NP2	PMSM	2024	150
Jaguar I-Pace	PMSM	2018	294
Kia EV6	PMSM	2021	239
Land Rover	SMR	2013	70
Mercedes-Benz EQE	PMSM	2021	215–505
Renault ZOE	EESM	2021	100
Tesla Model 3	IM (front) + IPM-SynRM (rear)	2020	366
Tesla Model Y	IM (front) + IPM-SynRM (rear)	2020	247
Volvo EX90	PMSM	2024	279–380
Xiaomi SU7	PMSM	2024	220–495



(**a**) (**b**) (**c**) (**d**)

Figure 3. Schematics of electric motors. (**a**) PMSM. (**b**) SRM. (**c**) IM. (**d**) PMaSynRM.

It is crucial to conduct an LCA of electric motors to accurately quantify the potential environmental impacts associated with EV traction motors. This assessment spans the entire lifecycle, from the extraction of raw materials such as copper and iron to the motor's end-of-life disposal, while also evaluating recycling potential and sustainability opportunities [44,45].

3. Traditional Materials for EV Traction Motors

3.1. Permanent Magnets

The majority of EV traction motors, as pointed out in Section 2, are based on the PMSM configuration. In this section, the materials currently used for PMs are analyzed, recalling that the ideal characteristics of a PM suited for EV traction motors are [22]:

- High value of the maximum energy product $(BH)_{max}$ [J/m^3], representing the maximum energy stored per unit volume,
- High value of H_c enables the magnet to resist demagnetization in the presence of external magnetic fields,
- High value of B_r. The higher the material B_r, the stronger the forces of magnetic attraction and repulsion that generate the driving torque,
- A low coercivity and remanence temperature coefficient.

The per-unit-volume losses due to the eddy currents can be expressed as:

$$p_{cp} = k_{cp} \frac{s^2 B_{max}^2 f^2}{\rho}, \quad (1)$$

where k_{cp} is a material constant, B_{max} is the maximum value of the magnetic induction, f is the frequency, s is a characteristic dimension of the component, and ρ the electric resistivity.

As illustrated in Figure 4, a major milestone in the development of magnets occurred around the 1940s with the invention of AlNiCo permanent magnets. AlNiCo refers to a family of iron-based alloys that incorporate aluminum (Al), nickel (Ni), and cobalt (Co). AlNiCo and ferrite magnets, however, are characterized by low values of $(BH)_{max}$. The true revolution in the magnet industry began in the 1970s with the development of rare earth element (REE)-based PMs. According to the International Union of Applied and Pure Chemistry, REEs are 17 elements in the periodic table corresponding to the 15 lanthanides plus the elements yttrium (Y) and scandium (Sc). REEs are generally subdivided into two main subgroups: light REEs (LREEs) and heavy REEs (HREEs) [46]. The revolution started with samarium-cobalt (SmCo) magnets, followed by neodymium-iron-boron (NdFeB) in the early 1980s, and samarium-iron-nitride (SmFeN) [21]. These advancements significantly enhanced magnetic performance, driving innovation and enabling modern applications.

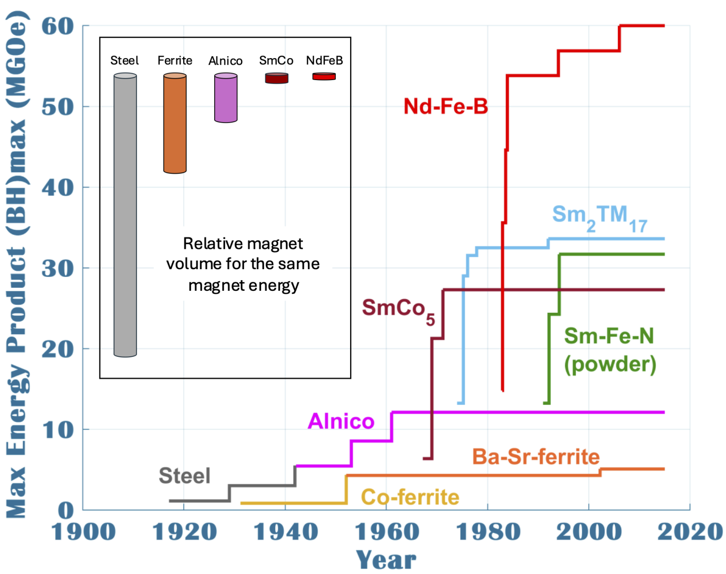


Figure 4. Timeline of materials for PMs and their maximum energy product [47].

The superiority of REE-based PMs becomes evident when considering the value of $(BH)_{max}$, justifying the use of REEs for the realization of PMs for electric traction motors. Table 2 provides a detailed overview of the key properties of traditional PM materials, highlighting their performance characteristics.

AlNiCo magnets have one of the highest Curie temperatures among permanent magnets, but their cost is relatively high due to the inclusion of cobalt. On the other hand, ferrite magnets are more affordable and distinguished by their high electrical resistivity, which minimizes eddy current losses as stated by Equation (1). SmCo magnets offer excellent thermal stability but are among the most expensive available. Nd-based magnets provide a cost-effective solution compared to other REE-containing magnets, offering high efficiency and magnetic density in a compact form, making them an ideal choice for applications requiring powerful performance at a relatively low cost.

Table 2. Properties of traditional PM materials [29].

Parameter	Fe	AlNiCo	SmCo	NdFeB
$(BH)_{max}$ [kJ/m^3]	8.35–31.8	10.7–71.6	130–240	220–421
Remanence B_r [T]	0.23–0.41	0.7–1.28	0.83–1.16	1.00–1.41
Coercive force H_c [kA/m]	50–290	37–143	480–840	760–1030
Density [kg/m^3]	4900	6800–7300	8400	7400
Electric resistivity [μΩm]	0.01	0.5–0.7	0.53–0.86	1.6
T_{max} [K]	523.15	773.15	573.15	423.15 [1]
T_{Curie} [K]	723.15	1133.15	1073.15	583.15
Price [USD/kg]	7.1	58	100	75

[1] Increased with the addition of Dy.

The Issue of Rare Earth Elements

Challenges related to REEs are widely discussed in research and remain a key concern for the EV industry [31,48]. Among all REEs, samarium (Sm), terbium (Tb), neodymium (Nd), and dysprosium (Dy) are currently used to manufacture high-performance PMs [36]. Sm and Nd are categorized as LREEs, while Tb and Dy are HREEs. More than 50% of the REEs global market is driven by PMs and catalysts, where the former is expected to increase in the next years due to the electrification campaign [49,50]. The REE content in SmCo magnets is approximately 22 to 40%, while for NdFeB magnets, 22 to 31% of Nd, 0.07 to 13% of promethium (Pr), and 0.77 to 4.2% of Dy are used [46]. In particular, Dy is added to NdFeB magnets to enhance their thermal stability, preventing demagnetization at higher temperatures [51]. It is worth mentioning that hybrid electric vehicles (HEVs) are one of the largest consumers of REEs [52]. Major REE content in HEVs is due to nickel-metal-hydride (NiMH) batteries and the hybrid transmission (motor and generator) [53].

The issue of using REEs extends beyond environmental sustainability, encompassing geopolitical concerns as well. A framework for assessing the environmental impact of a product is outlined in the Environmental Priority Strategies (EPS) system, which measures environmental burden in terms of environmental load units (ELU). One ELU corresponds to the environmental damage cost of one Euro. According to [54], Dy has the highest impact, with a score of 1500 ELU/kg, while Nd registers a lower score of 202 ELU/kg.

As shown in Figure 5, which depicts global rare-earth oxide (REO) production in 2023, China emerges as the dominant producer of REOs [55].

The dominance of China in the REE market (also known as the Chinese era) began around the early 1990s, following the decline of the Mountain Pass mine in California, largely due to environmental concerns and the inability to compete with the lower prices of REEs exported from China [56]. The risks of relying on a single dominant supplier became a major focus of research, especially after the 2011 REE crisis, which led to a sharp spike in prices [57,58].

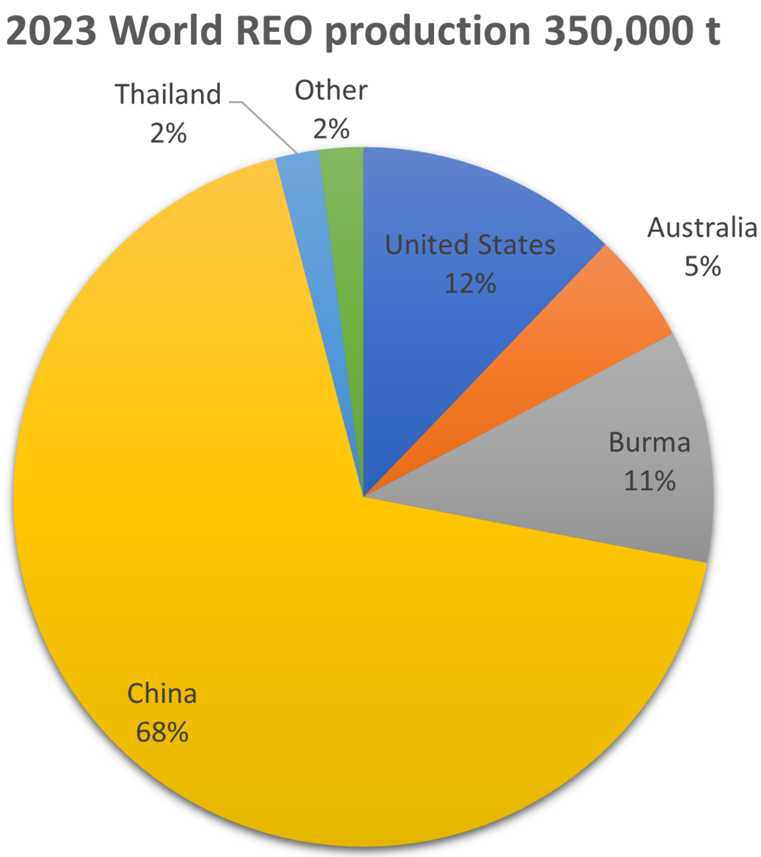


Figure 5. Distribution of global rare earth mine production in 2023. Data adapted from [55].

Beyond the economic impact of price volatility, there are significant social and environmental concerns related to REE mining. It is widely acknowledged that mining activities must be closely regulated to ensure worker safety and health [59–62]. These issues are particularly pressing for the European Union (EU), where the automotive industry is a major economic pillar. According to the European Commission, the EU relies on China for more than 90% of its REE supply [63], raising important questions about the future of its well-established automotive sector and its long-term supply chain security. In this scenario, the recycling technologies for REE-based PM are of great interest, as discussed in what follows.

The demand for REEs is projected to rise significantly in the coming years due to the ongoing electrification of the transportation and energy sectors. Although lanthanum (La) and cerium (Ce) are the most abundant REEs produced, the majority of demand is concentrated on Nd and Dy [64,65]. This imbalance may result in a supply shortage of Nd and Dy, prompting increased focus on the potential for recycling and recovering these critical elements from EoL products. In 2018, less than 1% of rare earth elements were recycled [65]. However, projections, as illustrated in Figure 6, suggest that recycled REEs will become a significant resource by 2030, playing a much larger role in meeting global demand [66]. A comprehensive review of the challenges surrounding REE recycling is provided in [67], where various methodologies for recycling REE magnets are explored. Notably, for magnets used in hybrid and electric vehicles, direct reuse is a potential option. However, the primary limitation is that these components have long service lifespans, meaning they are not yet available in large quantities as scrap for recycling. Generally, the approaches for REE recycling include [67]:

- Hydrometallurgical methods,
- Pyrometallurgical methods,
- Gas-phase extraction.

The description of these methods is out of the scope of the paper; the interested reader can find detailed information in [67–69]. A hydrogen-free mechanical-based recycling technique is recently proposed in [70].

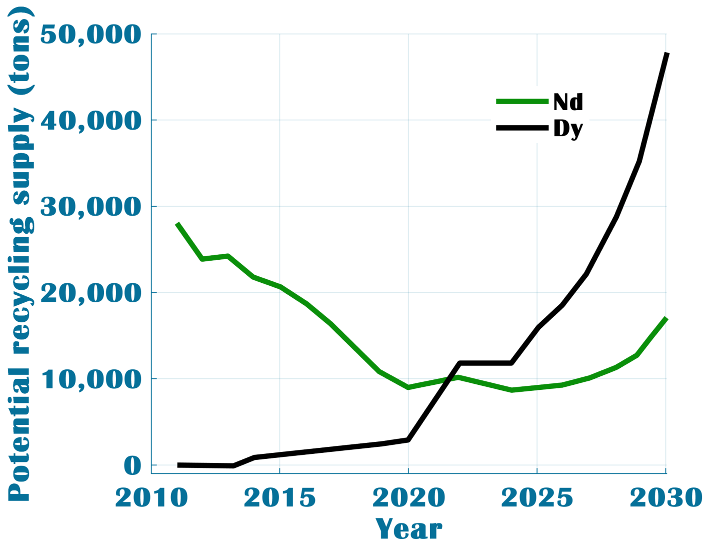


Figure 6. Potential recycling supply ratio for Nd and Dy. Data adapted from [66].

3.2. Ferromagnetic Core

In an EV traction motor, the ferromagnetic core serves the crucial function of confining and guiding magnetic flux. The material selected for this core must possess the following characteristics:

- High relative magnetic permeability μ_r, essential for effectively guiding magnetic flux and minimizing its dispersion,
- Low eddy current and hysteresis losses to increase overall efficiency,
- High magnetic saturation value B_s,
- Low coercivity value H_c,
- Thermal stability.

The materials that best lend themselves to the creation of the ferromagnetic core are those belonging to the family of soft ferromagnetic materials. Silicon (Si) (or electrical) steel, discovered in 1900, accounts for the major share of the global market because of its high values of B_s and μ_r. Electrical steel contains from 1% to 6% of Si, but the most common for the creation of the core of electric motors has 3.25% of Si content. The two most common types of electrical steel are grain-oriented and non-grain-oriented (NGO). NGO electrical steel is characterized by crystalline grains that are distributed randomly, without a preferential direction. This gives isotropic, i.e., uniform magnetic properties in all directions. It has higher core losses than grain-oriented electrical steel, making it very lossy when operating at high frequencies. However, it is easier to produce and cheaper (the approximate cost is about 950–1000 USD/ton). Currently, the NGO Si-iron (SiFe) is the preferred material for the realization of the ferromagnetic core of EV traction motors [24,71]. A summary of the properties of Si steel is given in Table 3.

Table 3. Properties of Si steel [72].

Parameter	Value
Density [kg/m^3]	7800
B_s [T]	1.8–2.1
$\mu_{r,max}$	40,000
Electrical resistivity [μΩm]	0.4–0.5
Coercive force H_c [A/m]	4

3.3. Windings

Since the early development of electric motors, copper (Cu) has been the predominant material for windings, thanks to its outstanding electrical conductivity, allowing the reduction of Joule losses, and strong mechanical properties. In contrast, aluminum (Al) has been used to a lesser extent, primarily in budget-friendly applications where minimizing the motor's weight is a priority. The key properties of Cu and Al are summarized in Table 4.

Table 4. Aluminum and copper properties.

Parameter	Cu	Al
Density [kg/m^3]	8960	2700
Electric resistivity [μΩcm]	0.0172	0.0265
Thermal conductivity [W/(mK)]	400	273
Breaking strength [MPa]	200	110

Al-based windings generally result in decreased torque performance [73]. However, in high-frequency, high-speed EV traction motors, the impact on overall machine efficiency is relatively minor since AC losses result in being lower than in copper winding [74–76].

Given the increasing electrification of the transport sector, extensive studies have been conducted to project the future global demand for copper [77]. Since 2000, copper has undergone large price increases, especially compared to aluminum. As can be seen from Figure 7, aluminum costs approximately four times less than copper per kilogram.

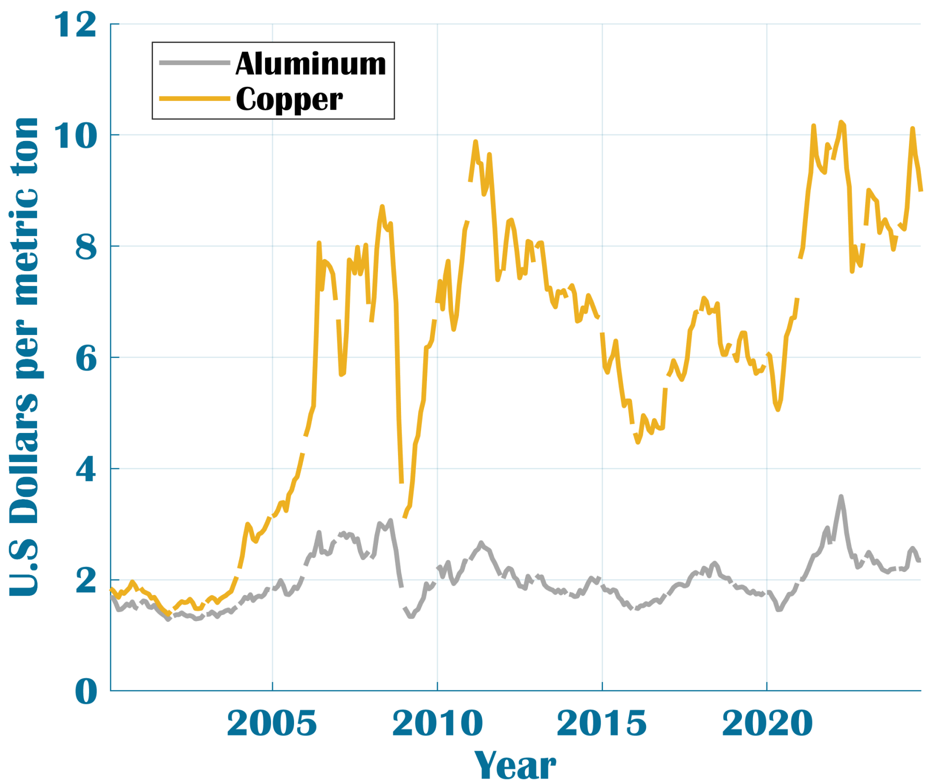


Figure 7. Global price of aluminum and copper from 2000 to today. Data adapted from [78].

The worldwide copper mine production in 2023 is illustrated in Figure 8. Alongside REEs, copper is identified as a high-risk material that could become a bottleneck in the transition to green technologies [79–81].

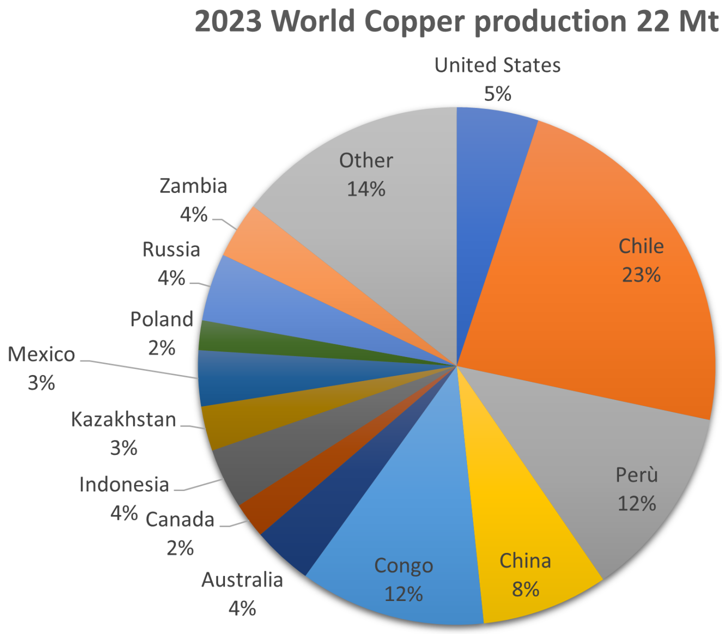


Figure 8. Distribution of global copper mine production in 2023. Data adapted from [82].

According to [54], copper ranks just behind REEs in environmental load in EV traction motors, scoring 131 ELU/kg. This high score is largely due to the environmental impact of copper mining, including the release of heavy metals and its limited availability [83].

The concept of sustainability is crucial for copper mining, particularly in GHG emissions associated with copper production [84]. To align with global efforts to reduce GHG emissions, recent years have seen a growing focus on the production of "green" copper, i.e., copper manufactured with a significantly lower environmental impact [85,86], e.g., as is the case of Chile mining companies using solar energy in their plants [87]. This initiative involves adopting cleaner energy sources and improving mining efficiency to minimize the ecological footprint of copper extraction and processing.

4. Emerging Materials for EV Traction Motors

4.1. Permanent Magnets

Given the challenges associated with the use of REEs for PMs, the current trend is shifting toward designing and manufacturing electric motors that utilize a reduced content of REEs or non-REE PMs. However, this transition is complex, as it necessitates sacrificing the exceptional magnetic properties afforded by SmCo and NdFeB. The need to substitute REEs for PMs is driven not only by global market dynamics, which are largely influenced by China, but also by significant environmental and toxicity concerns, as highlighted in Section 3.1. According to [35], NdFeB magnets, despite comprising less than 5% of an electric motor's total mass, account for approximately 25% of the motor's total GHG emissions. This underscores the substantial environmental impact of REEs in electrification technologies.

It is important to note that motor weight is a critical factor in the EV industry, making it particularly challenging to replace NdFeB magnets, which are characterized by very high $(BH)_{max}$. A detailed description of emerging materials for PMs is provided in [22,88], where three main candidates are highlighted. The first one is the SmFeN, in particular, $Sm_2Fe_{17}N_3$. This is a REE-based magnet; however, currently, Sm is less critical than Nd and Dy due to the lower demand [89]. SmFeN is characterized by high $(BH)_{max} \approx 470$ kJ/m^3, making it comparable to NdFeB magnets. Together with SmFeN, two non-REE magnets are identified: $Fe_{16}N_2$ and the mineral tetrataenite $L1_0$ FeNi [88,90]. For FeN, the theoretical value of $(BH)_{max}$ is about 1034 kJ/m^3; however, currently, it was demonstrated the possibility of producing FeN compounds with $(BH)_{max} \approx 159$ kJ/m^3 [22,91].

The potential of Mn-based compounds for EV traction motors has been explored [88,92]. A key advantage of this REE-free magnet is its estimated low cost of approximately 11 USD/kg [93], along with its higher values of B_r and H_c compared to ferrite magnets. The theoretical value of $(BH)_{max}$ is approximately 135 kJ/m^3 for the anisotropic low-temperature phase MnBi [94]. A significant drawback, which may pose challenges in the design of next-generation EV traction motors based on MnBi magnets, is the need to increase the motor size to match the performance of NdFeB-based motors [92].

A summary of the properties of emerging materials for PMs is listed in Table 5.

Table 5. Properties of emerging PM materials [94–96].

Parameter	SmFeN	FeN	$L1_0$ FeNi	MnBi
$(BH)_{max}$ [kJ/m^3]	470	159	446	135
Remanence B_r [T]	1.3	1.3	1.5	0.62
Coercive force H_c [kA/m]	884	300	100–200	510
T_{Curie} [K]	749	653	830	650

It is important to note that ferrite magnets can be used as a substitute for REE-based magnets [97,98]. Although they possess weaker magnetic properties than REE magnets, ferrite magnets remain highly appealing due to their lower cost, particularly for applications such as PMaSynRM [99].

4.2. Ferromagnetic Core

To reduce iron losses and enhance the efficiency of EV traction motors, thereby lowering energy consumption, alternative materials to electric steel are being actively explored. This topic is covered by many research papers [23,71]. Amorphous and nanocrystalline alloys, discovered at the end of 1960 and 1980, respectively, have recently attracted the attention of the realization of high-efficiency electric motors [100–102]. Amorphous materials, whose structure compared to that of steel is shown in Figure 9, are metals with a non-crystalline anisotropy. Amorphous metals such as Silicon-Iron-Boron (SiFeB) have higher resistivity if compared to SiFe alloys; however, there are still challenges in constructing complex geometries with these materials due to their low stiffness and elastic modulus [23,25]. The coercivity value of amorphous alloys, as listed in Table 6 for the case of the 0.0025 mm Amorphous METGLAS® 2605HB1M Alloy, can be around 2 A/m.

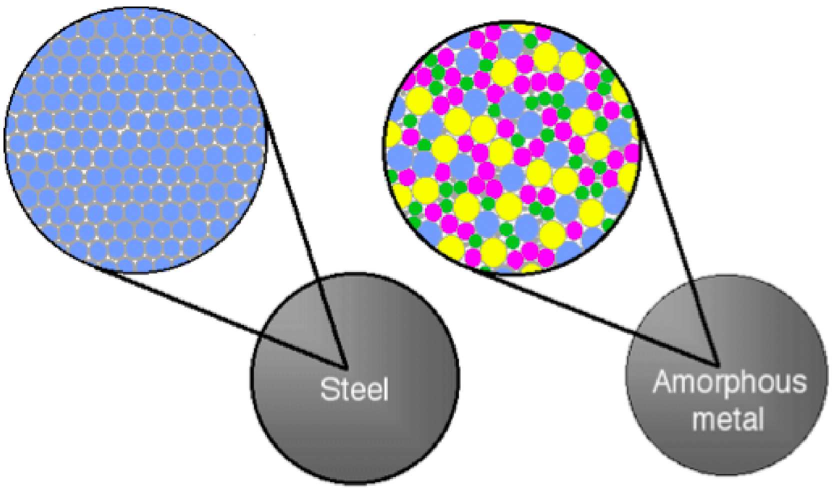


Figure 9. Structure of steel and amorphous metal [103].

In contrast to amorphous metals, nanocrystalline alloys exhibit a crystalline composition. Nanocrystalline alloys, such as the FINEMET® FeCuNbSiB, are characterized by a microstructure with small grains. FeCuNbSiB alloy has superior properties to cobalt-based amorphous alloy; however, the major drawback of FeCuNbSiB is its mechanical brittleness, which may limit its applicability to EV traction motors, even if some attempts have been recently made [104–106]. Moreover, nanocrystalline alloys are much more expensive than amorphous and SiFe alloys [101]. It is worth mentioning that the potential substitution of Nd with molybdenum (Mo) is analyzed in [107], bringing no notable differences.

Soft magnetic composites (SMCs) have attracted the attention of the research community since the 1990s due to their unique properties with several potential technological applications [108]. These materials are generally made up of iron powder on a micrometer scale. The particles are also coated with a thin electrical insulation layer. The advantage of handling powders is related to the possibility of generating complex 3-D geometries with advanced additive manufacturing techniques [109]. As listed in Table 6, the relative permeability of such materials is very low due to the presence of air gaps within the structure; however, their electrical resistivity is very high, thus suitable to reduce the losses. Generally, if compared to electrical steel, SMC materials have:

- Significantly lower relative magnetic permeability due to the presence of spaces of air in the compound,
- Higher hysteresis losses due to the mechanical stress that forms during the compaction process,
- Lower mechanical resistance, which makes the core more sensitive to permanent damage,
- Lower magnetic saturation flux density.

Table 6. Properties amorphous, nanocrystalline and SMC material [72,110–114].

Parameter	Amorphous METGLAS® 2605HB1M	Nanocrystalline FINEMET® FeCuNbSiB	SMC
Density [kg/m^3]	7300	7180	7300
B_s [T]	1.63	1.45	1.53
$\mu_{r,max}$	$6 \cdot 10^5$	$6 \cdot 10^4$–$6 \cdot 10^6$	950
Electrical resistivity [μΩm]	1.3	1.2–1.5	280
Coercive force H_c [A/m]	2.12	<10	200

Due to the substantial differences in properties between non-grain-oriented Si steel and SMCs, directly substituting a silicon steel core with an SMC core often leads to performance degradation, with only marginal improvements. However, recent research efforts have focused on enhancing material properties, optimizing production techniques, and exploring innovative core geometries to exploit the potential of SMCs [115].

Alongside SMCs, dual-phase materials developed by General Electric are also gaining attention [24,25,116]. A SynRM utilizing a dual-phase core material has been proposed, demonstrating competitive performance compared to Dy-free IPMs [117]. Dual-phase materials enable the variation of magnetic properties, such as permeability, across different regions through tailored manufacturing techniques [118].

4.3. Windings

The rising global demand for copper, its relatively high cost, and the push for improved performance have driven the search for innovative alternative materials. Among the most promising candidates at the forefront of scientific research are carbon nanotubes (CNTs), which have the potential to improve motor efficiency while maintaining cost-effectiveness significantly [119–121]. CNTs gained worldwide attention following Iijima's publication in 1991 [122]. CNTs have shown tremendous potential and, in recent years, have been considered as a possible replacement for copper in electric motor windings due to their exceptional mechanical, thermal, and electrical properties [123,124]. Structurally, CNTs are cylindrical formations with diameters on the micrometer scale, composed of carbon atoms arranged in a planar hexagonal lattice.

CNTs can be synthesized through five main processes: (i) arc discharge, (ii) laser ablation, (iii) electrolysis, (iv) sonochemical/hydrothermal, and (v) chemical vapor deposition (CVD) [125]. Where the latter is recognized as the most popular method for the production of CNTs. CNTs can be categorized into single-walled, double-walled, and multi-walled nanotubes.

As shown in Table 7, CNTs have a density approximately 6 times lower than that of copper, which could significantly reduce the weight of an electric motor if used in place of copper windings. Additionally, CNTs exhibit lower electrical resistivity than copper, potentially leading to a significant reduction in Joule losses and thus improving overall motor efficiency. It is worth noting that copper composite CNT, such as Cu-CNT, has recently garnered attention for its potential to enhance significantly the properties of the compound [126].

Table 7. Properties of CNT [127].

Parameter	Value
Density [kg/m^3]	1500
Electric resistivity [μΩm]	10^{-4}
Thermal conductivity [W/(mK)]	3000
Breaking strength [MPa]	1000

Despite their excellent thermal, electrical, and mechanical properties, CNTs have yet to be widely adopted in commercial electric motors and remain confined to research laboratories. The exceptional properties mentioned above are only observed in high-quality CNTs, which, at present, can only be produced in limited quantities and at a significant cost [128]. The synthesis of CNTs from bio-feedstocks and bio-derived compounds is discussed in [125]. The possibility of using biomaterials as precursors of CNTs is of great interest for the definition of a smart way to produce nanomaterials sustainably. The impact of CNTs on human health and the environment is the subject of study in many research papers [129–132], and the role of LCA is of central importance [133,134].

High-temperature superconductors (HTS) operating at higher temperatures than low-temperature superconductors, are very attractive for the construction of windings for future EV traction motors due to their negligible electrical resistivity. In literature, several research papers discuss the applicability of HTS for EVs [135–137]. Despite the significant advancements in HTS electric motors, challenges related to commercial viability persist. The design of HTS windings and cooling systems remains intricate, and the initial production and operational costs of HTS motor drives continue to be high.

5. Conclusions

This paper discusses the sustainability of traditional and emerging materials for the active parts of EV traction motors. As outlined in the previous sections, the PMSM based on NdFeB magnets, NGO SiFe iron core, and copper windings is the most common choice for EV traction motors. However, automakers are actively exploring alternative solutions to address environmental, economic, and political challenges. One of the main challenges remains how to create high-efficiency EV traction motors with REE-free permanent magnets. Together with REE-based magnets, the focus is also on the sustainability issues of copper-based windings. Even if copper itself can indeed be 100% recycled, several questions are posed concerning the relationship between global demand and recycling capabilities in the future.

Significant progress in electrical machines can only be achieved by embracing entirely new, breakthrough technologies. It is difficult to answer the question posed at the beginning of the article, on what the future configuration of EV motors looks like; indeed, as highlighted previously, the transition from traditional to novel materials is affected by many actors. From the previous analyses, it can be stated that the PMSM with an NGO SiFe core and copper windings will be the reference configuration for the electrification of the worldwide car park. The possibility of realizing optimized PMaSynRM without REEs is of great interest. Further research is needed before novel material solutions for permanent magnets, cores, and windings can be industrialized for use in EV traction motors.

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Abbreviations

The following abbreviations are used in this manuscript:

GHG	Greenhouse gas
ICEV	Internal combustion engine vehicle
IEA	International energy agency
EV	Electric vehicle
BEV	Battery electric vehicle
PHEV	Plug-in hybrid electric vehicle
LCA	Life cycle assessment
EoF	End of fife
PMSM	Permanent magnet synchronous motor
PM	Permanent magnet
SRM	Switched reluctance motor
IM	Induction motor
IPM	Interior permanent magnet
SynRM	Synchronous reluctance motor
PMaSynRM	Permanent magnet assisted synchronous reluctance motor
EESM	Externally excited synchronous motor
REE	Rare-earth element
LREE	Light rare-earth element
HREE	Heavy rare-earth element
HEV	Hybrid electric vehicles
EPS	Environmental priority strategies
ELU	Environmental load units
EU	European union
REO	Rare-earth oxide
NGO	Non-grain-oriented
SMC	Soft magnetic composite
CNT	Carbon nanotubes
HTS	High temperature superconductors

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