The Juxtaposition of Our Future Electrification Solutions

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Review

The Juxtaposition of Our Future Electrification Solutions: A View into the Unsustainable Life Cycle of the Permanent Magnet Electrical Machine

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Abstract: Electrification is increasing in prevalence due to the importance placed on it for achieving global net zero targets. This has led to the proliferation of electrical mobility, including the wide-scale production of passenger vehicles, personal mobility devices and recent announcements regarding electrically powered aircraft, as well as in energy production. Electrical machines provide a cleaner source of energy during operation in comparison to their traditional fossil-based alternatives. The uncertainty and lack of transparency hanging over these green credentials can be attributed to how these products are manufactured and then disposed of at the end of their life. For them to be a truly sustainable solution, improvements need to be made across their entire life cycle. With the projected increase in their numbers due to the advancement of electrification, this current life cycle is not sustainable, directly opposing the intention of these products. This paper will introduce the current demand and challenges. It will also present these motors broken down into their constituent parts and follow each through their typical lifecycle. This paper presents the typical current life cycle of permanent magnet electrical machines, demonstrating the environmental issues associated with the current linear life cycle, and proposing alternative practices, to ease the environmental burden.

Keywords: electrification; permanent magnet electrical machines; motors; sustainability; net zero; life cycle

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1. Introduction

Today, it is widely accepted that our choices as a society—moreover, as a species—are impacting our environment and climate [1,2]. Policy makers globally are introducing guidelines around modern topics such as sustainability, carbon neutrality and renewable energy in an effort to minimise the impact human activity is having on the planet. As we look to electrify the globe and achieve ambitious targets associated with these themes, has the sudden drive to push technology forward resulted in unsustainable choices?

In order to achieve climate policy targets, there is increasing pressure to move away from fossil fuels and towards electrification due to the reduction in CO_2 emissions [3]. As such, an increase in the uptake of electric transport [4] and renewable energy [5,6] is expected. For these key electrification products, the manufacturing routes and end of life processes are under intense scrutiny for many component parts such as the lithium-ion batteries in electric vehicles (EVs) [7], wind turbine blades [6,8] and permanent magnets within electrical machines [9]. In addition to climate concerns, rare earth elements used in these machines have faced supply chain issues—a decade ago, the cost of neodymium increased by approximately 350% over a period of only two years, resulting in global fears of a material shortage and production lull [10]. This economic concern has led to new production avenues being explored, ranging from recovering material from end of life (EoL) machines to the exploration of new mining sites for virgin material extraction [9,11].

The issue of sustainability within electrical machines is a fast-evolving landscape, with the drive for increased production of higher performance machines at odds with the slow rate of implementation of sustainable design alternatives. This juxtaposition represents a real risk in terms of both future end of life processing challenges, and material supply shortages. If the machines that will come into service within the next decade are not designed with sustainability in mind, then the impact of this decision will inevitably be felt well before the 2050 net zero target deadlines. Industry is then running the risk of managing a large influx of machines at the end of their service life that have been not designed for recirculation, whilst also navigating new concerns such as limited raw material markets and growing production targets.

Permanent magnet electrical machines (PMEMs) are in a somewhat unique and juxtaposed position of being linear in their lifespans but used in future electrification products that are heralded as green, eco-friendly, net-zero solutions. There is not currently a cohesive viewpoint from the electrical machine community on what should be done from a sustainability point of view, since the focus is on technological advances for future applications, rather than the long-term sustainable practices. This community uncertainty will lead to a higher risk of unsustainable product decisions being reinforced and repeated for the foreseeable future. Whilst there are existing studies outlining life cycle assessment (LCA) of PMEMs [12–14], none of these have made their way into common design practices, and there is still a long way to go in bringing all the current research in this area together as a coherent framework for change.

This paper will outline in depth each stage of the PMEM component life from raw material sourcing to end of life to serve as a benchmark for current practices, to inform the electrical machine community of the sustainability challenges facing the sector, and opportunities to focus on the relevant areas for improvement. This approach, by looking at the entire life cycle of all common PMEM components, is unique in the literature.

2. Drivers

There are several drivers for improving sustainability, generally arising from climate change concerns. Concentrating on the UK, these would include carbon net zero, transportation targets and energy goals [15]. The 2015 Paris Agreement has encouraged national policies and strategies aimed at achieving net zero carbon emissions. “Net zero”, “carbon net zero” and “zero CO_2” are terms used to describe the target of balancing the greenhouse gas emissions produced through human activity with the amount being removed from the atmosphere [16,17]. The UK government has set a target of 2050 for this to be achieved, whilst the Scottish government are aiming for 2045 [18]. To achieve net zero, governments are setting more specific targets and deadlines, as are industry bodies and representatives in individual businesses. For example, many businesses are moving their fleet to EVs to eliminate exhaust emissions or putting in place carbon capture technology within their production lines.

In relation to the electrification of transportation, the UK government has put in place a ban on new petrol or diesel car and van sales from 2030, and on zero-emission hybrid car and vans from 2035. As such, they have earmarked approximately GBP 2.5 billion to encourage drivers to switch to EVs, including funding rapid charge points in public and commercial places as well as private homes, and supporting R&D projects looking for electrification and hydrogen powered solutions [19,20]. Consumers are already demonstrating a shift towards electrification ahead of the ban. In the years between 2016 and 2022, UK sales of EVs (battery electric and plug-in hybrid) have increased almost ten-fold from 39,000 to 317,600, and this is projected to double to 637,000 by 2027 [21]. Between 2021 and 2022, plug-in hybrid vehicle sales reduced by approximately 11.5%, but battery electric increased by over 40%, whilst sales of petrol and diesel cars also decreased by 10.4% and 38.9%, respectively [22]. For 2022, Tesla accounted for almost a fifth of all battery electric vehicle sales in the UK. As a company, Tesla has seen significant growth in recent years, with a 20% increase in production between Q3 and Q4 of 2022, and a 44% annual increase from 2021 [23].

When looking at heavy goods vehicles, zero emission targets are set at 2035 for vehicles up to and including 26 tonnes) and 2040 for those larger than 26 tonnes. However, moving into public transportation such as buses and trains, the expectation from government becomes less mandated. Whilst the government has intentions to fund and invest in zero emission buses, they have not set dated targets for the industry. Instead, the industry itself is setting its own targets, with a number of operators aiming to add only zero or near-zero emission buses to their fleet from as early as 2025. For rail, the UK government has committed to providing a net zero rail network by 2050 but has not put in place specific targets in the years leading up to this deadline, only ambitions such as removing diesel-only trains from use by 2040 [24,25].

The Aerospace Technology Institute (ATI) has released a roadmap outlining sustainability within aviation, in support of the International Civil Aviation Organisation (ICAO) and other aviation organisations who are looking at the industry's environmental performance. Between them, there are a number of targets including decarbonising aircraft taxiing, reducing CO_2 and NOx emissions during flight and increasing the recyclability of the aircraft itself [26]. This coincides with the use of sustainable aviation fuels (SAFs) as an alternative to fossil-based fuels, and the emergence of electric and hydrogen powered aircraft [27]. The UK government has also set a target of 2030 for the offshore wind energy fleet to produce enough energy to supply each household in the country [28], and a 2035 target of an entirely renewable-powered electricity grid [29]. Projections suggest that approximately 2600 new turbines will be required by 2030 in order to achieve these targets [30]. Growth of the key markets for electrification of transport and energy is necessary to achieve the ambitious net-zero targets outlined by the government and its agency bodies. However, the rapid development and manufacture of the products will provide sustainability challenges [31] that will need to be overcome to ensure a sustainable long-term future for PMEMs.

3. Permanent Magnet Electrical Machine Overview

Although almost all electrical machines are reliant on electromagnetism and use magnetic material to varying degrees, not all incorporate a permanent magnet (PM). PMs are commonly embedded into the rotor, creating a constant magnetic field, whilst conductive copper wire is wound around the stator teeth. When being used as a motor, current is applied through the windings, which provides an opposing magnetic field to the one provided by the magnets themselves. These act upon each other, causing the rotor core to rotate. As a generator, the movement of the rotor core generates a current within the windings. PMEMs are often used in larger applications where exact movement is critical, such as EVs [32].

The conventional configuration, as shown in Figure 1, is the most common and a practical application of the system [33], not least because the design lends itself to facilitating heat removal from the externally mounted windings whilst keeping the rotating components enclosed. The outer rotor configuration is more commonly used in applications where it becomes an integrated component of the larger product, such as in ventilation fans and hard disk drives [34]. That said, axial flux permanent magnet (AFPM) machines are an up-and-coming alternative to the traditional configuration due to the different spatial requirements of the machine. Due to their flat shape, they can be used as a flywheel in some applications, making them popular in some industrial equipment and machinery [35]. Typically, the components of electrical machines are split into two groups: electromagnetically active and non-active. The active components include the windings, magnets, and stator laminations, and the non-actives include the rotor shaft, containment sleeve and housings. Each of these components will now be discussed in more detail.

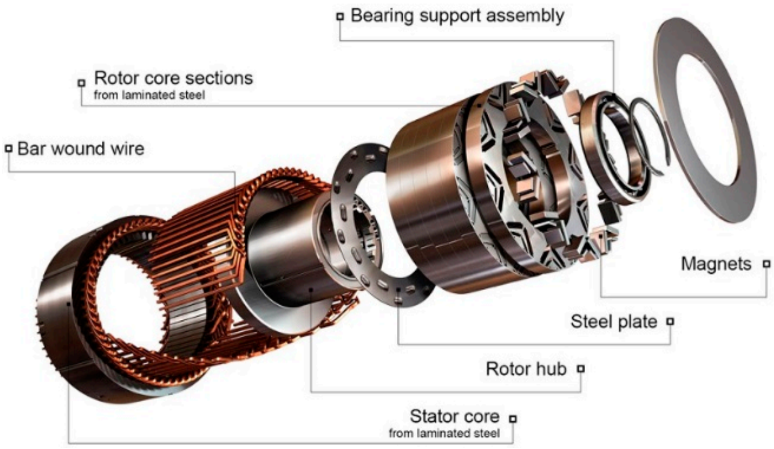

Figure 1. Exploded view of PMEM [33].

3.1. Rotor

The rotor core (also known as the back iron) is typically a solid structure of steel, although it can be made using laminations. The piece may be manufactured as a solid in high-speed applications as it increases the capability to cope with the mechanical and thermal stresses put on it when rotating. Ferromagnetic alloys are often used in this application due to the mechanical strength and electromagnetic characteristics of these materials. The most common is carbon steel. There are vast arrays of carbon steel with various compositions of materials exhibiting different properties, selected based on cost, performance and application. For example, AISI 1010 is over 99% iron with carbon, manganese, silicon, phosphorus and sulphur making up the remaining maximum 0.92%, whilst Fe52 steel uses 1.5% manganese [36]. Aho et al. [36] performed an analysis on eight potential ferromagnetic alloys to demonstrate the mechanical and magnetic properties of the materials when used as a rotor core, suggesting that whilst the low carbon steel Fe52 is most commonly used and perfectly functional, there are suitable alternatives.

3.2. Stator

The stator core is typically constructed using laminations of silicon steel [37,38]. Silicon steel, also known as electrical steel, is an iron alloy with a variable silicon content. The silicon content is typically around 3%, but extensive testing has demonstrated that a 6.5% content is optimal for minimal iron losses and maximal magnetic permeability [39,40], which are two of the properties desired from the material for its use in stators. The primary concern, however, with 6.5% silicon content is the brittleness of the material, although research is currently underway to try and improve the manufacturability of high-silicon-content steels [41]. The composition of the alloy provides many different grades of the product, and the use of the grades is dependent on the product requirements and cost. Other materials can be used as an alternative to silicon steel, such as cold-rolled steel, cobalt iron or nickel iron. Each of these materials would still typically be used to form laminations making up the core stack, although the material selected would be due to its desired properties. For example, cobalt iron, which is a soft magnetic alloy, may be selected due its superior magnetic saturation and low losses whilst working at high speeds [42].

3.3. Windings

Stator windings are, most commonly, made from copper. Copper has long been recognised as an excellent conductor and is used extensively in electronics and heating. Copper is drawn into wire, which is then wound around the teeth of the stator, creating coils. Hollow coils are an alternative to traditional wire and are designed to aid cooling of the coils [43]. Modern additive manufacturing methods can also be used to create concentrated copper coils [44], although coils manufactured using this method currently have poorer electrical conductivity than drawn copper [45].

Many alternatives to copper have been considered, including silver and gold. Silver has a better conductivity than copper, but the cost of the raw material is much higher [46]. Aluminium has been also considered as a more cost-effective alternative [46], but it has a lower conductivity; therefore, aluminium windings must have more turns or have a greater diameter than the copper alternative [47] or be coated in copper [46]. More windings or larger diameter coils leads to larger, heavier components, which require more raw material usage. Although it is possible to match the efficiency between both materials, it is much more common to see copper used in this function than aluminium.

3.4. Magnets

The properties of all the raw materials being incorporated into the final component are critical to the magnet's functionality. Through the years, various materials have been used for the magnets within PMEMs in an effort to increase the performance or to improve on the criterion for the PM, namely anisotropy, Curie temperature and ease of magnetisation [48]. This continual supersession of materials has allowed for drastic improvement in these areas and provided for greater variation in application, including the likes of EVs [32].

Neodymium–Iron–Boron (NdFeB)-based magnets are most commonly used in modern PMEMs. These were simultaneously invented in 1984 by Sumitomo Special Metals Co. in Osaka, Japan and General Motors Corp. in Detroit, MI, USA. Both had a similar composition with a high energy density and coercivity and were adopted quickly, overtaking the then-popular Samarium–Cobalt (SmCo) magnets. This was because the materials utilised similar production methods, but NdFeB had a lower cost due to the inexpensive iron content [49]. NdFeB magnets are also light, considerably more so than alternative magnet-type Aluminium–Nickel–Cobalt (AlNiCo), which makes them a good option for machines where weight is a key driver [48]. NdFeB magnets do, however, have some disadvantages. The material has a lower Curie temperature than SmCo and therefore a lower working temperature. To combat this, cobalt can be incorporated into the blend, although that in turn increases costs. The magnets are also vulnerable to corrosion and are almost always plated or coated, adding another stage and expense to the production [50]. In recent years, the cost of the rare earths that make up the composition of the magnet have increased [32]. Neodymium can make up only a small percentage of the composition of the magnet, although, according to German [51], the ideal content of neodymium is 26 wt.% whilst for the sintering manufacturing process (discussed in detail later in this paper), 30–33 wt.% is optimal. There have been various percentage make ups of metals to form these high-functioning magnets, and the exact compositions are dependent on the grade of the alloy required [52]. That said, the most common elements included in the product composition are neodymium, iron, boron, cobalt, cerium, dysprosium and praseodymium, although aluminium, gadolinium, niobium, and others may also be used. Dysprosium and praseodymium are used to replace some of the neodymium to improve the corrosion resistance and improve the intrinsic coercivity of the material [53].

3.5. Housing and End Caps

The housing is most commonly made up of a main body and two end caps, which typically would be bolted and/or welded together. One or both end caps may feature an in-built fan to assist with air cooling the PMEM. These can be made of any number of materials, including aluminium, steel or plastic [54]. For electrification products, it is likely the end caps will be steel whilst the housing may be steel or aluminium—although aluminium has a light-weighting advantage and is therefore desirable [55]. These components are most likely sand casted or extruded, depending on the profile and complexity of the design.

3.6. Shaft

The rotor shaft passes through the centre of the machine to allow the rotational function, allowing the interaction between magnets and windings. These can be made from any number of materials, depending on the product application. Mild steel is used on many lower-grade shafts, but for high strength requirements (such as in electrification products), it is more likely to be an alloy steel using materials such as vanadium, chromium, nickel and/or cobalt [56] as well as carbon, manganese, phosphorous and sulphur. This is likely to be forged into the cylindrical profile, either through extrusion or, more likely, radial forging to allow for some complexity in the design [57].

3.7. Containment Sleeve

Magnets can be integrated to the rotor either by the rotor having slots cut through it, which the magnets are slotted into (interior magnets), or have slots etched to the exterior, which magnets will sit within (surface mounted) [58]. Often, a containment sleeve may be used to ensure surface mounted magnets are not deformed by radial forces from the rotating machine and to avoid surface damage and over-stress of the magnets. This is most often a carbon or glass–fibre composite or a metal alloy such as Inconel, due to being magnetically inert materials [59]. Inconel is likely to be more prevalent in electrification solutions due to its higher thermal properties [60]. To be effective, there must be an interference fit between the sleeve and the rotor with mounted magnets. Inconel sleeves can be manufactured in a variety of ways, including machining a forged bar, creating a lamination stack [59], or bending and welding sheet material.

3.8. Material Summary

In relation to the applications and areas of interest for high-value PMEMs outlined in the above assessment, Table 1 lists the most common materials currently used.

Table 1. Potential Material Compositions of PMEM Active Components.

Component Part	Material(s) of Interest	Elements within Compound
Rotor Core	Carbon steel alloys	Iron, Manganese, Silicon, Phosphorous, Sulphur
Stator Core	Silicon steel	Iron, Manganese, Silicon
	Steel alloys	Iron, Cobalt, Nickel, Chromium, Manganese, Silicon, Vanadium, Niobium, Phosphorous, Sulphur
Windings	Copper	Copper
Magnets	NdFeB	Neodymium, Iron, Boron, Cobalt, Cerium, Dysprosium, Praseodymium, Aluminium, Gadolinium, Niobium
Housing	Aluminium	Aluminium
End Caps	Steel	Iron
Shaft	Steel alloys (SAE 1045)	Iron, Vanadium, Chromium, Nickel, Cobalt, Manganese, Phosphorous, Sulphur
Containment Sleeve	Carbon fibre	N/A
	Inconel	Nickel, Chromium, Aluminium, Cobalt, Copper, Iron

Discussed in the introduction was the supply chain concerns, particularly with elements such as neodymium and dysprosium. However, what is not to be ignored is the criticality of these elements on their own accord based on the availability of the finite materials across the globe. Mineral-based materials such as the elements used in PMEM components are becoming more readily used in household and industrial products, increasing demand [61]. Whilst criticality can be based on the supply and demand balance—whether something is in regular or irregular demand is a factor of its own—it can also be determined by the overall availability of the materials based on what is known of their prevalence in the earth [62].

Table 2 compiles results from various sources [63–65] to provide an assessment on the criticality of the elements needed for PMEM production, based on both perspectives towards the term "criticality".

Table 2. Criticality of Elements Based on Supply [63–65].

Component Part	Material(s) of Interest	Increased Threat to Supply	Limited Availability	Not Currently Threatened
Rotor Core	Carbon steel alloys		Manganese, Phosphorous	Iron, Silicon, Sulphur
Stator Core	Silicon steel		Manganese	Iron, Silicon
	Steel alloys	Chromium, Cobalt	Manganese, Niobium, Phosphorous, Vanadium, Nickel	Iron, Silicon, Sulphur
Windings	Copper		Copper	
Magnets	NdFeB	Cobalt, Dysprosium	Niobium, Neodymium, Boron	Aluminium, Cerium, Gadolinium, Iron, Praseodymium
Housing	Aluminium			Aluminium
End Caps	Steel			Iron
Shaft	Steel alloys (SAE 1045)	Chromium, Cobalt	Vanadium, Nickel, Manganese, Phosphorous	Iron, Sulphur
Containment Sleeve	Inconel	Chromium, Cobalt	Nickel, Copper	Aluminium, Iron

Figures 2 and 3 outline the weight percentages of the components within example PMEM products and the equivalent weight by the percentage of each metallic element, respectively. Whilst these are not standardised and there will be variation across different machines, the charts provide a visual example of one possible composition. Figure 3 presents data on the approximate weights of each material, extracted from several sources [36,66–68].

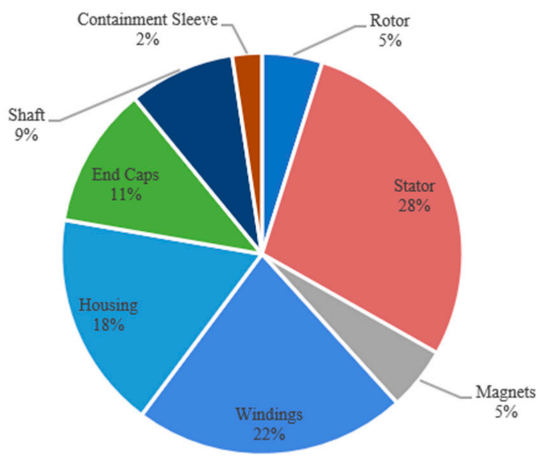

Figure 2. Composition of a PMEM by weight of component in an aero-engine starter generator [55].

This results in approximately 26% of materials used within high-value PMEMs having some concerns with the criticality to the supply, although only 0.49% is at increased threat. This suggests that alternatives should be sought, either to the way the elements are circulated to preserve virgin stock or to the composition of the materials used in these components. This section has highlighted materials that have criticality concerns associated with them, but it is also worth noting that all of the materials within the electrical machine are finite resources. If the increasing rate in manufacture of electrical machine is not balanced by resource efficiency and recycling goals, then virgin material sources will likely be unable to cope with the constantly increasing demand.

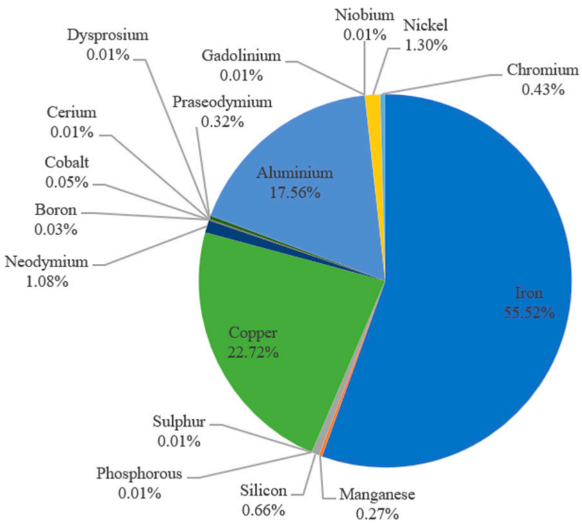

Figure 3. Percentage of each metal by weight used in PMEM components, compiled from data collected in [36,66–68].

4. Current Standard Life Cycle of a PMEM

As discussed in the introduction, growth within electrification areas will be required to meet net zero goals, but the current manufacturing methods have a lot of room for improvement in order to provide a fully sustainable pathway to net zero. This section will summarise the standard life cycle of PMEMs, whilst highlighting some of the key environmental issues associated with these products. Most metals will follow a similar production path as demonstrated in Figure 4. Although the refinement and manufacturing routes may differ, the principles of forming the relevant alloys and composite materials are similar.

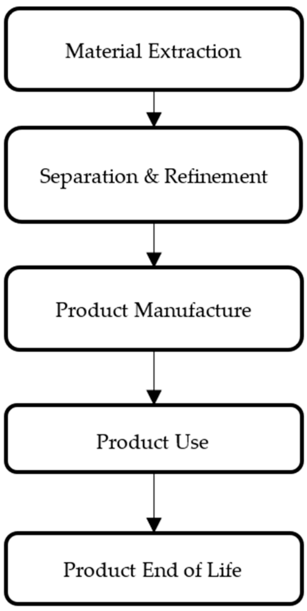

Figure 4. Generic product life flow chart.

4.1. Material Extraction

There is no doubt that, over the decades, mining has been an important part of economies worldwide [69]. The materials extracted from the earth by mining have proven crucial in the production of consumer goods over a great many industries, allowing for development, growth and employment. In many developing countries, mining contributes greatly to the employment rates and GDP, as well as being a contributing factor when looking for foreign investment [70]. However, there are also negative impacts from mining, affecting the environment and human health. These are outlined in Table 3. There are three primary operation methods—surface, underground and in situ leach (ISL)—all of which go through exploration and site development before undergoing various levels of drilling and blasting in order to extract the ore, with ISL also requiring chemical leaching of the land to extract the ore. The method(s) chosen depends on a number of factors, such as the grade of the desired material, the geology, the area topography, the amount available, potential profit and the site location [71]. These are explored further in Table 4.

While mining poses a significant environmental challenge, there are a number of approaches and technologies that can reduce the impact of such operations. The use of electrification in extraction and transportation is a logical step, as is the avoidance of road transportation in preference to rail or pipelines. Industrial symbiosis should be prioritised in respect to the waste streams associated with mining operations, to ensure key minerals/materials are captured and do not negatively impact the location around the mining site. Currently, operational H&S procedures and closure plans for mines are not consistent between countries, which can lead to detrimental practices being carried out, which negatively impacts the local ecology and workforce. Standardisation of practices, with best principles in mind, would improve the conditions of mining sites and ensure better conformity across the globe. A key driver for change could be the movement within the industry for greener portfolios [72].

Table 3. Mining Site Life Stages.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Exploration	• Critical in establishing the potential material reserve in area. • Non-invasive and invasive methods can be used to determine feasibility. • Repeated over large site footprint. • Typically takes ten years for these stages.	[73,74]	• Lengthy process requiring multiple visits (transportation, infrastructure). • Potentially disruptive over a vast area
Detail site design	• Performed alongside exploration stage. • Studies and assessments include planning for mine closure, workforce, infrastructure, environment, mine design, mining methods and economics. • Assessments and data from exploration determine viability of mine.	[73–75]	• Should include environmental planning, i.e., wastes, pollutants, closure, in line with national and local requirements such as Environmental Protection Agencies or Acts

Table 3. *Cont.*

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Construction and operation	• Mine would be open as long as possible but can vary from 2 to 100 years depending on volume and value of material. • Value can be difficult to predict due to the length of time between assessment and ore mining.	[73,74]	• Each mining method can be environmentally disruptive, including wastes, transport, infrastructure, pollutants, and noise.
Closure	• At the end of the mine's usable lifetime, it is decommissioned and closed. • Environmental management systems are in place, but land reclamation is a difficult, time-consuming task.	[73,74,76,77]	• Closure plan should be in place. • Land reclamation is very difficult to achieve, particularly for open pit mining where the land has been removed.

Table 4. Mining Operations Assessment.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Surface mining	• Methods of mining whereby the earth is removed in layers to reach the deposits. • Explosives, drilling and machine digging can be used to create this sub-terrain structure.	[78,79]	• Very disruptive—removing all local eco-systems by removing surface layers of earth. • Pollution and toxicity from tailings and dust.
Underground	• All underground mining involves digging shafts or tunnels into the earth to reach the ore in the sub-surface.	[74]	• Caution needed to prevent cave-in of mining shafts and tunnels. • Less disruptive on surface level. • Increased dangers to workforce.
In-situ	• Involves drilling a circuit of boreholes into the area of land, then injecting these with a chemical liquid to dissolve solid deposits. • Pressure used to pump the solution through the circuit, capturing the ore.	[80,81]	• Can be used after other mining methods to try to capture any ore not already removed. • Leakage of the chemical solution into surrounding land—toxicity.

4.2. Ore Separation and Refinement

Numerous methods are available for separation and refinement of individual elements from ore. Depending on the desired material and methods available, the number of processes applied will vary [82]. The separation and refinement of the ore is a very complex process, requiring multiple methods and machines with many iterations in each in order to create a high-purity raw material. In almost all instances, the ore removed from the earth will typically be large rock forms, which require crushing into smaller parts before grinding into a fine powder for further processing [83]. Although there are many possible processes, some of the most common are covered in Table 5. Whilst the processes shown in this paper only outline a few of the available options, the effort and energy required to separate and refine individual elements from mined ore is apparent. An array of machinery, chemicals, power and heat sources are required, which can all pose issues.

Table 5. Ore Separation and Refinement Assessment.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Ore roasting	• Ore oxidised within furnaces at temperatures exceeding 1000 °C. • Can happen repeatedly throughout the refinement process.	[84,85]	• Energy intensive process with heat/energy waste. • Pollutants from combustion process.
Electromagnetic separation	• Used on highly magnetic ore such as monazite and bastnäsite. • The material is spread on a magnetic rolling belt, separating the magnetic from nonmagnetic particles.	[82]	• Magnetic material required to create belt.
Floatation	• Ground powder is submerged in liquid chemical solutions. • Air is pumped, capturing the lighter particles in the bubbles to skim and separate.	[82]	• Toxicity from chemical solution waste. • Energy use and resultant pollution from air compression system.
Solvent extraction	• Chemical leaching processes where concentrated ore is dissolved in varying chemical solutions repeatedly to increase purity.	[81,83,85]	• Toxicity from chemical solution waste.

Some of these methods have been used for many decades and are industry standard for the processing of the materials. However, there have been technological advances in ore refinement, which may recover greater quantities of elements from the ore being refined [86]. By increasing the yield per tonne of ore, less material will be considered waste, which already contributes significantly to waste streams globally [87]. Whilst some material may be kept to backfill mining operations when completed, others may be sold to secondary industries (such as rocks and soil to the construction sector). Increasingly, tailings and slag as being used in concrete or road production. However, inevitably, there will be hazardous waste produced that cannot be recycled [88]. By replacing virgin material with recycled content in products, there is less burden on finite resources to enable future electrification targets. Steel and copper, for example, are already widely recycled and utilised in new product manufacture. Using recycled steel rather than virgin materials can reduce energy consumption by up to 74% and is the equivalent of saving 1.5 tonnes of iron ore being mined, 1.28 tonnes of waste being produced, and air and water emissions of approximately 80% [89]. Whilst some material recycling is still in its infancy—that of magnets, for example—there are clear improvements to be made across the product manufacture by investing in recycling strategies and utilising existing recycled stock.

4.3. Product Manufacture

Magnets are typically manufactured in one of two ways: bonding or sintering. Bonding is a less common method than sintering; it combines different material blends with various non-magnetic binding agents, typically through one of four processing routes—calendering, extrusion, injection moulding and compression [90]. Sintering creates one solid product by fusing particles at temperature and/or under pressure [51] as part of a complex manufacturing process, outlined in Table 6. Bonded magnet processing can produce near-net shape products requiring little to no finishing operations, which is a key advantage over sintered magnets, as shown in Table 7. The process also allows for complexity in the magnet's shape and offers more flexibility in the flux output for any given magnet. However, sintering can provide a higher flux output and operating temperature magnet than the bonded process.

Table 6. Sintered Magnet Manufacture Assessment.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental issues
Vacuum induced furnace	• Prevents oxidation of metals during heating process. • Raw materials melted at incredibly high temperatures to create molten metal alloy. • Alloy cooled to form flakes or ingots.	[51,91,92]	• Used most often to produce magnets. • Very energy intensive due to the heat and vacuum environments required. • Requires additional gases to produce block (argon, nitrogen, hydrogen). • Finishing methods required, creating waste magnetic material. • Pollutants from combustion processes.
Hydrogen processing	• Hydrogen decrepitation: ingot placed in hydrogen atmosphere, which is absorbed, causes expansion, generates stress and breaks ingot down into pieces. • Hydrogen disproportional desorption/dehydrogenation recombination: dependent on phase change of alloy powder—ingot placed within hydrogen vacuum at temperature before being quenched in argon.	[53,92–97]	
Milling	• Within nitrogen and argon atmosphere. • Milled by jet to remove hydrogen and create fine powdered alloy.	[95]	
Pressing	• Die cast: material compressed in axial or transverse direction with external magnetic field applied parallel to compacting force. • Isostatic/rubber isostatic pressing: material compressed in mould by pressurised fluid with external magnetic field applied.	[98–101]	
Green magnet	• Block demagnetised before release from mould by pulse.	[100]	

Table 6. *Cont.*

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental issues
Sintering, quenching and machining	• Block in sintered furnace at 1060 °C, liquifying material to increase density. • Quenched to minimise unwanted phase changes in material. • Diamond cutting tools required to machine block. • The swarf created from the machining is combustible—cooling liquid required throughout to prevent spontaneous combustion.	[92,98,100]	• Used most often to produce magnets. • Very energy intensive due to the heat and vacuum environments required. • Requires additional gases to produce block (argon, nitrogen, hydrogen). • Finishing methods required, creating waste magnetic material. • Pollutants from combustion processes.
Magnetism	• External magnetic field applied to permanently magnetise block.	[100]	
Coating/Plating	• Prevents oxidation of magnetic block. • Coated in nickel, zinc alloys, gold, silver, tin, etc.	[92,98,100, 102,103]	

Table 7. Bonded Magnet Manufacture Assessment.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Calendering	• Material is heated to a resin. • Fed through multiple heated rollers which compress material, forming sheets.	[90]	• Can have reduced Dy content than sintered but must be a larger volume for same technical outputs. • Simpler, faster manufacturing methods to sintering equivalent, making them less energy intensive. • Performance of bonded magnets is lower than sintered, which is why they are used less.
Extrusion	• Material heated and drawn through machine by extrusion screw. • Forced through shaped die and can then be cut to length.		
Injection moulding	• Material drawn into heated chamber by injection screw. • Forced into mould to create shape profile.		
Compression moulding	• Magnetic powder put through liquid binder. • Material compound compressed under pressure.		

The recycling of magnets has been a focus of research in recent years and, subsequently, there has been success in magnet recycling capability [104]. However, repurposing of magnets would be a more attractive solution than recycling within the circular economy hierarchy, as it is less energy intensive and does not require the material to be taken back to a base state. Alternative forms of manufacture may also be considered for improving the sustainability of these magnet. For example, additive manufacturing is being explored particularly as an alternative to some of the bonded magnet processes [105]. Redesign of components could also assist with the reuse of magnets in secondary applications. Högberg et al. presented a case study for the direct reuse of magnets from a 3 MW direct drive wind turbine generator, by making use of a segmented design [106]. Looking at cross-industrial markets could allow for repurposing of magnets into downstream applications, with the use of expertise to ensure quality of the product is maintained. An additional difficulty with magnets is the material composition, as well as the array of sizes, shapes, and coatings used. Whilst magnets are designed or selected based on their expected performance within a product, incorporating some standardisation would be beneficial for sustainable manufacturing, reuse in secondary applications, and efficient recycling streams. The current design of magnets is optimised for in-use performance, but EOL processing can be extremely difficult. For example, most magnets are glued in place- whether they are surface mounted or interior inserted. In addition, the size of magnets that will need to be removed for electrical machines will present major logistical issues. In some wind turbine applications, the magnets can be up to 1 m in length, with an aggregated weight of 2 tonnes [107]. Implementing design for disassembly procedures will be essential in the design of future products to ensure that a streamlined, economical end of life process will be feasible.

Windings will focus on copper as it is the primary material of choice. Copper is predominantly drawn into the wire that is used in windings. The wire is then covered with an insulating coating such as plastic or enamel, with resins often used to impregnate the stator assembly once the coils are wound in place, as outlined in Table 8.

Table 8. Copper Winding Manufacturing Assessment.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Drawing	• Metallurgical extrusion. • Copper molten and drawn through machine, between rollers or through dies, until at desired profile.	[108]	• Energy requirement to heat copper. • Subsequent heat losses.
Winding	• Insulation of wire. • Winding into stator.		• Improved insulation materials. • Improved fill factor (through better winding techniques).
Encapsulation	• Potting or encapsulation with resins.		• Resin makes life difficult for EOL.

Potential improvements in the sustainability of windings could be made on several fronts, including design, manufacturing, and assembly. The use of hollow coil conductors is used in larger applications to allow for direct cooling of the windings, and if implemented in a wider range of applications, could lead to an improved fill factor (and, hence, improved performance) and the removal of external cooling requirements [43]. Additive manufacture is also being investigated as a small-batch manufacturing option for complex, non-uniform windings [45]. The use of additive manufacturing for coil windings has several advantages including the design of compact end windings, the potential to achieve higher power densities, and the opportunities to include localised cooling of the coils. The current disadvantages include a lower IACS rating—approximately 88% [109]—and the scalability of the process for large-volume, economical production.

One of the largest environmental gains that could be achieved in the windings of electrical machines is the removal of resins. Encapsulation of the stator winding is included as a standard stage for most high-value machines produced currently, with the resins providing several functions, including thermal dispensation, electrical insulation, mechanical stiffness, and protection from external environmental influences. Although the coil resins provide many benefits during the in-use phase, they cause difficulty when disassembling the machine and add complexity to the recovery of material. If resins could be removed from the stator windings, or new resins are developed that are easier to remove at the EOL stage, then this would aid disassembly activities and thus enable easier implementation of circular economy strategies such as repair or remanufacture.

The stator core is most often built up of electrical steel sheets, which are cold rolled to thickness. These sheets are stamped into the required shape before being laminated together. This is discussed in Table 9. The rotor core is generally manufactured by hot forging carbon steel into the cylindrical blank of the size required. Holes for the shaft and slots for the magnets are then stamped, along with any other details required, as outlined in Table 10.

Table 9. Stator Core Manufacturing Assessment.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Cold rolling	• Heat the material and then cool it to room temperature before rolling. • Rolling a sheet through compression rollers to make it thinner. • Rolling will be repeated to produce the final thickness (typically between 0.2 and 0.4 mm per lamination).	[110]	• Potential heat and energy waste from heating process. • Energy use due to multiple rolling stages
Lamination	• Sheets held together at exact intervals either by adhesive, fusion welding, or a mechanical fixture such as doweling.	[111,112]	• Non-reversible processes prevent end of life recovery
Stamping	• Part put under pressure where sections are pushed out to create desired profile.	[113]	• Physical waste from stamping which cannot be easily recovered. • Energy intensive process.

Table 10. Rotor Core Manufacturing Assessment.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Hot forging	• Material heated to approximately 75% of melting temperature, making it malleable. • Billet worked into required shape by processes such as extrusion and pressing.	[114,115]	• Energy intensive process with heat/energy waste. • Pollutants from combustion process.
Stamping	• Part put under pressure where sections are pushed out to create desired profile.	[113]	• Physical waste from stamping which cannot be easily recovered. • Energy intensive process.

Two of the key issues associated with stator and rotor laminations are the yield losses incurred during profile stamping/cutting and the loss of material value in the recycling process. Several alternative options exist to reduce yield losses, including redesign of components in order to minimise the distance between components when cutting, research into new clamping techniques as a means to reduce wasted cutting space, and prioritising families of components across a company's entire product range. Another sustainability issue associated with stator and rotor core production is the loss of high-value materials during the recycling process. Recycling of steel is an established industry in the EU, with approximately 100 million tonnes of scrap steel recycled every year. This equates to 56% of the steel produced in the EU steel coming from recycled sources [116]. Electrical steels are a high-value material and go through more processing stages than standard steel grades, which leads to higher costs and longer lead times. When the scrap electrical steel is collected after stator and rotor core profiling, this highly processed, expensive material is recycled in a general steel recycling stream. A value-added activity would be to consider a closed loop recycling system in order to maintain the higher value of this specific material.

The end caps are typically steel, cast into shape. The housing may also be cast steel, although if the profile is simple, these may be extruded. Aluminium is often used as a lightweight alternative to steel for these components. These processes are explored in Table 11. The shaft which passes through the rotor is likely to be an alloy steel in the applications of concern in this paper. As such, radial forging would be employed to allow a changeable profile, as discussed in Table 12. The containment sleeve is likely to be Inconel due to the high-performance requirements of electrification PMEMs and may be forged from a solid bar as outlined in Table 13.

Table 11. Housing/End Cap Manufacturing Assessment.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Casting	• Steel melted slowly in induction furnace. • Poured into compact sand mould and allowed to cool.	[117]	• Scrap and waste materials (of the correct composition) can be feedstock. • Energy intensive process with heat/energy waste.
Annealing/Heat treatment	• Part heated to just above critical temperature (for composition). • Allowed to cool.	[117]	• Energy intensive process with heat/energy waste. • Improves ductility and toughness of material, improving machinability.

Table 12. Shaft Manufacturing Assessment.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Radial forging	• Material billet heated to deformation temperature. • Billet guided through machine and areas put under compression by hammers.	[118]	• Energy intensive process with heat/energy waste.

Table 13. Inconel Containment Sleeve Manufacturing Assessment.

Sub-Stage	Sub-Stage Description	References	Key Points and Environmental Issues
Forged bar	• Material billet heated to deformation temperature. • Billet hammered or pressed with dies. • Machined whilst at high temperature to create tube.	[57,119]	• Energy intensive process with heat/energy waste. • High material waste from machining.

Typically, the non-active components of an electrical machine account for 45–55% of the total weight, with these components not directly contributing to the power density of the machine. Their design and manufacture have also not been a priority, as research has focused on the improvement and optimisation of the active components, such as the windings and stator core. Several improvements could be made to the non-active components by considering alternative designs and manufacturing methods. One area of focus could be the use of near-net-shape (NNS) manufacturing preforms and processes where possible. Current manufacturing routes often include the use of bulk forgings or castings, which are then machined to the final geometry, resulting in high material wastage. The use of NNS processes can result in a reduction in cost and wastage, especially when high-value materials are required. Many NNS processes are also conducted at room temperature, which leads to grain refinement and therefore improved mechanical properties within the final component. An increase in mechanical properties can then facilitate a lightweight design, which can lead to energy savings during the in-use phase of the machine. As discussed in detail earlier, the increased use of recycled material was presented as a way to improve the sustainable production of electrical machines. Since the non-active components are mainly required for mechanical stability and external environmental protection, they are an ideal candidate for increasing the content of recycled materials. Steel, aluminium, and titanium are readily recycled within industry, and electrical machine manufacturers could benefit from this existing infrastructure.

The methods of assembly can be separated into two categories: reversible and non-reversible. Reversible processes include fixings, mechanical fasteners and interference fits, such as between the magnets and the rotor core when the magnets are integrated. Non-reversible processes include welding, resins and adhesives, often used to attach magnets to the rotor when surface mounted, for example. These must include design for maintenance, disassembly, and easier EOL processing.

4.4. In Use

Given that the focus of this research is with regard to future electrification solutions, two widely used PMEM products are electric vehicles and wind turbines. The average age of a vehicle on the road is 8–10 years, whilst the age of cars at scrappage is approximately 14 years [120,121]. Wind turbines have a life expectancy of 20 to 25 years, although current extension programmes are looking to keep turbines in service for 30 years or longer, depending on a number of factors such as their efficiency at site and maintenance requirements [122]. PMEMs will be designed for a specific application, with an assumed efficiency rating based on the variables assessed [123]. However, there are factors that can impact this working efficiency during use, such as working outside of the projected temperature range, insufficient air flow for cooling, overheating of the unit, excessive vibration from poor/degrading installation, electrical overload and contamination [124,125]. This can contribute to a degradation in performance of a product over its lifespan, with Staffell and Green [126] concluding that the output from an onshore wind farm decreases by an average of 1.6% per year. There is now a move to embed sensors within the turbine to provide real-time data, allowing for a more accurate assessment of the machine performance and subsequently allowing for pro-active maintenance [127]. Designing for the implementation of sensors and understanding what data need to be collected during the in-use phase will be crucial for the successful implementation of an optimised end of life strategy. In order for the full power of the circular economy to be realised, the correct intervention strategy must be implemented at the right time, and this will only be possible if the operating cycles of the machine can be traced and analysed. A comprehensive data collection strategy would also allow for predictive maintenance, which would assist with asset life extension. Ensuring a maintenance strategy is developed at the design stage, and stringently followed per manufacturer guidelines, will go a long way to ensure the longevity of high-value electrical machines and allow for preventative maintenance strategies to be employed. A comprehensive maintenance strategy will also provide opportunities for asset life extension, making use of embedded sensors to ensure product performance beyond the designed lifetime.

4.5. End of Life

Whilst some PMEMs may be disassembled by specialist recyclers, many will be disposed of as electrical waste since the technologies capable of recycling the complex components within PMEMs are not at a stage where they are commercially feasible or economically viable [12]. Concentrating on the UK, this lack of supply chain is not aided by the lack of appropriate waste streams available, as the treatment facilities across the countries vary in technology and capability [128]. The most common method of recycling PMEMs that is classified as electrical waste is shredding [129]. This process cuts the machine into smaller pieces and then sorts them into their base materials. However, this process does have a risk of contamination in the waste that results in lower-grade material outputs. Given the high value of some of the materials (for example, the silicon steel and cobalt iron used in the rotor and stator laminations), the lack of separation and salvaging of the individual materials is not only a quality or environmental loss but also a financial one. Larger PMEMs may be disassembled rather than shredded due to the fact they are simply too oversized for the shredding machinery. Disassembly would allow for a greater opportunity for reuse or recycling of the steels, for example, without as much risk of contamination as seen in the shredding method. However, due to the methods of assembly, it is possible that components can be damaged and therefore not suitable for reuse. This is particularly noticeable in copper windings, which are precoated with an insulating material, wound tightly onto the stator teeth and then commonly coated in resin, making it almost impossible to separate and unwind. Even so, the coating is subject to degradation, and, for this reason, it is common practice to recycle the windings rather than attempt any kind or reuse.

If the magnets are surrounded by a containment sleeve, this will have to be cut off due to the interference fit design and therefore cannot be directly reused. There are some commercially available recycling processes for carbon fibre, although this industry and an appropriate supply chain is still in its infancy and the majority of EoL carbon fibre will be disposed of rather than recycled [130]. The magnets themselves can also be damaged due to the design—for example, where the magnet is integrated to the rotor rather than surface mounted. Whilst some magnets may be reused, such as those from wind turbines due to the size [131], the majority will be waste or could potentially be recycled. Currently there is little recycling of magnets, although this is being carried out to some extent in China [132], and there are currently efforts to develop magnet recycling elsewhere [133,134]. With future targets requiring an increase in production volume, the use of the current materials already within the UK will need to be utilised to ease the strain on production of virgin stock and limit the unpredictability of the supply chain. High-value recycling streams could assist in retaining the value of key materials such as rare earth magnets and electrical steel. These streams will be complex to implement, and the challenge is bigger than a single sector; hence, a cross-sectoral approach will be required to make this economically and technologically feasible. For asset life extension, repair and remanufacturing activities to be fully utilised in PMEMs, design for disassembly will need to be a priority, and sustainability factors will need to be on par with performance and cost when designing future machines. Design for disassembly includes design choices such as the elimination of non-reversible assembly techniques in order to facilitate easy dismantling in any relevant waste stream.

In line with the zero-waste hierarchy, reuse of products is considered more beneficial than other practices; therefore, considering potential second use opportunities for the machine at the design stage could lead to significant reductions in the environmental footprint of these products. Potential second life opportunities could include reuse of the complete machine in the same primary application, or repurposing of the machine in secondary, downstream applications. These opportunities will need to be considered fully at the design stage, with a cross-sectoral approach in mind, as a lack of forward planning will likely make secondary use highly improbable.

Whilst the responsibility for this end-of-life management may lie with different parties (i.e., the manufacturer, consumer, decommissioner or otherwise), having the infrastructure available to manage these different products will be critical. Ideally, the end-of-life would be considered at the design stage and "built in" at the manufacturing stage, i.e., by manufacturing with disassembly potential in mind so that materials can be recirculated at end-of-life through appropriate channels, reducing resource depletion and embedded emission impact.

4.6. Transportation and Packaging

An aspect of the entire life cycle of the product not discussed above is transportation requirements. There are many stages over the life of the product where the materials and components will require transportation on a global scale for PMEMs, as shown in Figure 5. The supply chain of PMEMs is complex because of this, typically with multiple modes of transport required and a variety of (often single-use) packaging used, all of which has an environmental impact [135].

For example, NdFeB magnets are composed of more than ten individual materials, all of which must be mined. This is a global operation due to the availability of the ore, with neodymium primarily sourced in China, niobium mainly found in Brazil, iron mined in Australia, and so forth. The ore will be transported from where it is mined to where it is refined, and packaged, such as in powder or billet form. All these materials must then be transported to one location and mixed into the composition required, before finally being manufactured into the magnet. Magnets are likely sold business to business and will thus be transported again to the assembly site, before being sent to the distribution centre and then onto the customer. To overcome some of these challenges, creating localised markets would be a potential solution. Having closed loop recycling of materials in-house or within a local area to reduce virgin stock could reduce transportation costs and the associated environmental impact. Where virgin stock is required, localising the source location of this could also be advantageous from a transportation perspective. For example, whilst Australia is one of the highest producers of iron, it is mined in many other countries—selecting the one closest would reduce the impact of transportation whilst potentially also reducing costs and time. Contracting parts or manufacturing to external companies is not uncommon, but optimising the network of these could also have a positive effect. For example, rolls of sheet metal material may be manufactured in Asia or South America, shipped to Europe for component manufacture (i.e., stamping or laser cutting of laminations), and then shipped elsewhere for assembly before being sent to the company's distribution location(s), whilst other component parts make similar global journeys for use in the final assembly. Re-considering each of the suppliers, their locations and making steps to reduce the number of stages or at least the distance over which parts are travelling could reduce impact and time. Utilising LCA to provide a baseline for current practices and having greater transparency of these operations could be beneficial to this exercise. In relation to the packing, utilising existing standardised products such as crates and pallets where possible, without single-use wrapping, would be beneficial. Minimising single-use packaging or replacing it with reusable, recyclable or compostable alternatives should be feasible due to the variety available today.

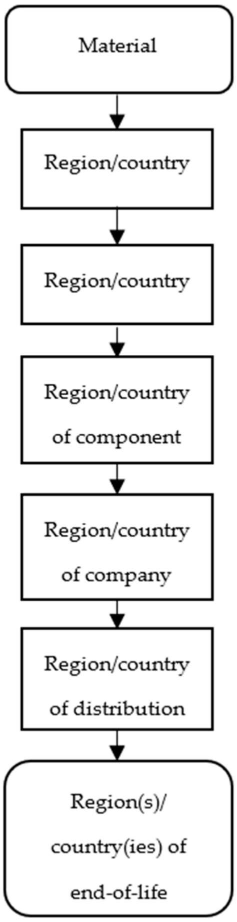

Figure 5. Material transportation flow chart.

5. Discussion

Electrification is increasing at a rapid rate, heralded as a key solution for achieving carbon net zero targets. Whilst PMEMs are already prevalent in everyday products, the expanse of renewables and EVs (including automotive, bus, rail and aviation) to replace the more traditional options will undoubtedly increase the volume of demand for these machines. This paper has described in depth the different life cycle stages of the PMEM, demonstrating where some of the environmental burden from these products lies. With the mining of virgin material from mineral ore, the machinery requires damage to the local ecosystem and pollution, as well as raising concerns regarding the increased reliance upon an at-risk stock of finite supply. Refining the ore is a wasteful process, likely to be energy intensive and producing toxic by-products. The manufacturing processes have been shown to be complex, energy and heat intensive, and often requiring chemicals. The in-use phase of the product, whilst performing a function related to sustainable activities, may have inefficiencies. There are few options at the end-of-life stage for these products—the material is unlikely to be reused and, if recycled, the complexity of the original composition is likely to be lost as the material enters general stock (i.e., steel). The embedded carbon within each product does not appear to be a consideration in the discussion of future electrification solutions, where an increase in both the volume and power of electrical machines will be required to meet demand. It is, however, undoubtedly a challenge that can be reduced with some foresight, design changes and a shift in mindset. Considering aspects such as designing for disassembly would go a long way to reducing the waste material at end of life, for example. Using recycled rather than virgin materials would reduce the reliance of virgin stock and would thus lead to a reduced risk of market fluctuation or shortages, while lowering the environmental impact of the product.

6. Conclusions

This paper has identified several issues across the life cycle of the machine and serves as the basis for the next steps in order to reduce the environmental impact of PMEMS given their rapid proliferation into new markets. There are opportunities for incremental, yet significant, changes to be undertaken including applying new design approaches that consider the disassembly and end-of-life aspects of the product.

Electrification of different industries such as transportation and energy are important if global net zero targets are to be realized; however, it is short-sighted to view EVs and wind turbines as the panacea to human climate impact challenges.

This paper has shown that the current linear cycle for PMEMs is clearly not sustainable given the relatively high usage of critical materials. A more circular approach is needed that can include design for end-of-life management, close loop recycling of metals and composites, and the application of novel manufacturing techniques such as additive manufacturing for high-value components including magnets.

This paper has served to demonstrate what this typical life cycle looks like whilst highlighting some key problem areas in relation to the environmental impact. The outputs from this paper will serve as a basis for future work, which will endeavour to provide alternative manufacturing routes for electrical machine components, with an emphasis on resource efficiency and sustainable manufacturing practices.

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References

1. Cook, J.; Oreskes, N.; Doran, P.T.; Anderegg, W.R.; Verheggen, B.; Maibach, E.W.; Carlton, J.S.; Lewandowsky, S.; Skuce, A.G.; Green, S.A.; et al. Consensus on Consensus: A Synthesis of Consensus Estimates on Human-Caused Global Warming. *Environ. Res. Lett.* **2016**, *11*, 048002. [CrossRef]
2. Hausfather, Z. Analysis: Why Scientists Think 100F of Global Warming is due to Humans. Carbon Brief. 2017. Available online: https://www.carbonbrief.org/analysis-why-scientists-think-100-of-global-warming-is-due-to-humans/ (accessed on 9 June 2023).
3. Cleary, K. Electrification 101. Resources Future. 2019. Available online: https://www.rff.org/publications/explainers/electrification-101/ (accessed on 9 June 2023).
4. Zhang, R.; Fujimori, S. The Role of Transport Electrification in Global Climate Change Mitigation Scenarios. *Environ. Res. Lett.* **2020**, *15*, 034019. [CrossRef]
5. Knopf, B.; Nahmmacher, P.; Schmid, E. The European Renewable Energy Target for 2030—An Impact Assessment of the Electricity Sector. *Energy Policy* **2015**, *85*, 50–60. [CrossRef]
6. Lefeuvre, A.; Garnier, S.; Jacquemin, L.; Pillain, B.; Sonnemann, G. Aniticipating In-Use Stocks of Carbon Fibre Reinforced Polymers and Related Waste Generated by the Wind Power Sector until 2050. *Resour. Conserv. Recycl.* **2019**, *141*, 30–39. [CrossRef]
7. Woollacott, E. Electric Cars: What Will Happen to All the Dead Batteries? BBC. 27 April 2021. Available online: https://www.bbc.co.uk/news/business-56574779 (accessed on 9 June 2023).
8. Mishnaevsky, L. Sustainable End-of-Life Management of Wind Turbine Blades: Overview of Current and Coming Solutions. *Materials* **2021**, *14*, 1124. [CrossRef]

9. Yang, Y.; Walton, A.; Sheridan, R.; Guth, K.; Gauss, R.; Gutfleisch, O.; Buchert, M.; Steenari, B.-M.; Gerven, T.V.; Jones, P.T.; et al. REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review. *J. Sustain. Metall.* **2017**, *3*, 122–149. [CrossRef]
10. Canals, C. The Curious Case of Rare Earth: A Non-Crisis. CaixaBank Research. 2014. Available online: https://www.caixabankresearch.com/en/economics-markets/commodities/curious-case-rare-earth-non-crisis (accessed on 9 June 2023).
11. Binnemans, K.; Jones, P.T.; Müller, T.; Yurramendi, L. Rare Earths and the Balance Problem: How to Deal with Changing Markets? *J. Sustain. Metall.* **2018**, *4*, 126–146. [CrossRef]
12. Bailey, G.; Mancheri, N.; Van Acker, K. Sustainability of Permanent Rare Earth Magnet Motors in (H)EV Industry. *J. Sustain. Metall.* **2017**, *3*, 611–626. [CrossRef]
13. Rassõlkin, A.; Belahcen, A.; Kallaste, A.; Vaimann, T.; Lukichev, D.V.; Orlova, S.; Heidari, H.; Asad, B.; Acedo, J.P. *Life Cycle Analysis of Electrical Motor-Drive System Based on Electrical Machine Type*; Estonian Academy of Sciences: Tallinn, Estonia, 2020. [CrossRef]
14. Hernandez, M.; Messagie, M.; Hegazy, O. Environmental Impact of Traction Electric Motors for Electric Vehicle Applications. *Int. J. Life Cycle Assess.* **2017**, *22*, 54–65. [CrossRef]
15. UK Government Implementing the Sustainable Development Goals. UK Government. 2021. Available online: https://www.gov.uk/government/publications/implementing-the-sustainable-development-goals/implementing-the-sustainable-development-goals--2 (accessed on 10 August 2023).
16. Energy Saving Trust What Is Net Zero and How Can We Get There? 20 October 2021. Available online: https://energysavingtrust.org.uk/what-is-net-zero-and-how-can-we-get-there/ (accessed on 10 January 2022).
17. Delafield, G.; Donnison, C.; Roddis, P.; Arvanitopoulous, T.; Sfyridis, A.; Dunnett, S.; Ball, T.; Logan, K. Conceptual Framework for Balancing Society and Nature in Net-Zero Energy Transitions. *Environ. Sci. Policy* **2021**, *125*, 189–201. [CrossRef]
18. Scottish Government Climate Change. Energy and Climate Change Directorate. 2019. Available online: https://www.gov.scot/about/how-government-is-run/directorates/energy-and-climate-change/ (accessed on 10 June 2023).
19. APC UK. New £50 m Funding from Government and Industry Accelerates Automotive Bid to Reach Zero Carbon. 16 October 2019. Available online: https://www.apcuk.co.uk/new-50m-funding-from-government-and-industry-accelerates-automotive-bid-to-reach-zero-carbon/ (accessed on 10 January 2022).
20. UK Government. Government Takes Historic Step towards Net-Zero with End of Sale of New Petrol and Diesel Cars by 2030. 18 November 2020. Available online: https://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030 (accessed on 10 January 2022).
21. Statista Electric Vehicles. May 2023. Available online: https://www.statista.com/outlook/mmo/electric-vehicles/united-kingdom#unit-sales (accessed on 1 June 2023).
22. The Society of Motor Manufacturers and Traders Car Registrations. May 2023. Available online: https://smmt.co.uk/vehicle-data/car-registrations/ (accessed on 1 June 2023).
23. Statista Number of Tesla Vehicles Produced Worldwide from 1st Quarter 2016 to 4th Quarter 2022. January 2023. Available online: https://www.statista.com/statistics/715421/tesla-quarterly-vehicle-production/ (accessed on 1 June 2023).
24. Department for Transport. *Decarbonising Transport: A Better, Greener Britain*; The Crown: London, UK, 2021.
25. Lyons, G.; Curry, A.; Rohr, C. *Decarbonising UK Transport: Final Report and Technology Roadmaps*; Report to the UK Department for Transport; Mott MacDonald and Partners: London, UK, 2021.
26. ATI INSIGHT. *Sustainable Aviation: ATI Framework*; ATI: Swampscott, MA, USA, 2020.
27. Airbus Sustainability. 2021. Available online: https://www.airbus.com/en/sustainability (accessed on 10 January 2022).
28. UK Government. New Plan to Make UK World Leader in Green Energy. 6 October 2020. Available online: https://www.gov.uk/government/news/new-plans-to-make-uk-world-leader-in-green-energy (accessed on 10 January 2022).
29. George, S. UK Government Firms up 100% Clean Electricity Target for 2035. 8 October 2021. Available online: https://www.edie.net/news/11/UK-Government-firms-up-100--clean-electricity-target-for-2035/ (accessed on 10 January 2022).
30. Bourne, S. Can the UK Achieve Its' 50 GW Offshore Wind Target by 2030? 10 May 2022. Available online: https://www.dnv.com/article/can-the-uk-achieve-its-50-gw-offshore-wind-target-by-2030--224379 (accessed on 21 February 2023).
31. Mopidevi, S.; Narasipuram, R.; Aemalla, S.; Rajan, H. E-mobility: Impacts and analysis of future transportation electrification market in economic, renewable energy and infrastructure perspective. *Int. J. Powertrains* **2022**, *11*, 264–284. [CrossRef]
32. Chau, K. *Electric Vehicle Machines and Drives: Design, Analysis and Application*; John Wiley & Sons: Singapore, 2015. [CrossRef]
33. The Engineering Knowledge Permanent Magnet Synchronous Motor. 7 December 2019. Available online: https://www.theengineeringknowledge.com/permanent-magnet-synchronous-motor/ (accessed on 26 January 2022).
34. Kumaravelu, U.D.; Yakub, S.M. Mohamed Yakub Simulation of Outer Rotor Permanent Magnet Brushless DC Motor Using Finite Element Method for Torque Improvement. *Model. Simul. Eng.* **2012**, *2012*, 961212. [CrossRef]
35. JGieras, F.; Wang, R.-J.; Kamper, M.J. *Axial Flux Permanent Magnet Brushless Machines*; Springer: Dordrecht, The Netherlands, 2008. [CrossRef]
36. Aho, T.; Sihvo, V.; Nerg, J.; Pyrhonen, J. Rotor Materials for Medium-Speed Solid-Rotor Induction Motors. In Proceedings of the IEEE International Electric Machines & Drives Conference, Antalya, Turkey, 14 May 2007. [CrossRef]

37. Scheerlinck, B.; Sergeant, P. Comparison of Motor Stator Teeth Built of Soft Magnetic Composite and Laminated Silicon Steel Sheets in an Axial Flux Permanent Magnet Synchronous Machines. In Proceedings of the IEEE International Magnetics Conference, Beijing, China, 11–15 May 2015. [CrossRef]
38. Matsui, T.; Yun, K.J.D.-W. Magnetic Properties of Silicon Steel Sheet Core with Different Processing Stress. In Proceedings of the International Conference on Metal Material Processes and Manufacturing, Jeju Island, South Korea, 19–20 July 2018. [CrossRef]
39. Kenjo, T. *Permanent Magnet and Brushless DC Motors*; Clarendon Press: New York, NY, USA, 1985.
40. Takajo, S.; Hiratani, T.; Okubo, T.; Takajo, S.Y.O.; Hiratani, T.; Okubo, T.; Oda, Y. Effect of Silicon Content on Iron Loss and Magnetic Domain Structure of Grain-Oriented Electrical Steel Sheet. *IEEE Trans. Magn.* **2018**, *54*, 1–6. [CrossRef]
41. Li, H.Z.; Liu, Z.Y.; Wang, X.L.; Ren, H.M.; Li, C.G.; Cao, G.M.; Wang, G.D. {114}[481] Annealing Texture in Twin-Roll Casting Non-Oriented 6.5 wt% Si Electrical Steel. *J. Mater. Sci.* **2017**, *52*, 247–259. [CrossRef]
42. Liu, H.; Chow, L.; Wu, T. Design of a Permanent Magnet Motor with Wide Temperature Range. In Proceedings of the ECON 2015—41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, Japan, 9–12 November 2015; ISBN 978-1-4799-1762-4.
43. Luvata Hollow Conductors. Available online: https://www.luvata.com/Products/Hollow-Conductors/ (accessed on 28 June 2021).
44. Wrobel, R.; Mecrow, B. A Comprehensive Review of Additive Manufacturing in Construction of Electrical Machines. *IEEE Trans. Energy Convers.* **2020**, *35*, 1054–1064. [CrossRef]
45. Simpson, N.; North, D.; Collins, S.; Mellor, P. Additive Manufacturing of Shaped Profile Windings for Minimal AC Loss in Electrical Machines. *IEEE Trans. Ind. Appl.* **2020**, *56*, 2510–2519. [CrossRef]
46. Hagedorn, J.; Blanc, F.S.-L.; Fleischer, J.B.F.S.-L.; Hagedorn, J.; Fleischer, J. *Handbook of Coil Winding: Technologies for Efficient Electrical Wound Products and Their Automated Production*; Springer: Berlin/Heidelberg, Germany, 2017. [CrossRef]
47. Kimiabeigi, M.; Widmer, J.; Sheridan, R.; Walton, A.; Harris, R. Design of High Performance Traction Motors Using Cheaper Grade of Materials. In Proceedings of the 8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016), Stevenage, UK, 19–21 April 2016. [CrossRef]
48. Pan, S. *Rare Earth Permanent-Magnet Alloys' High Temperature Phase Transformation: In Situ and Dynamic Observation and its Application in Material Design*; Springer: Berlin/Heidelberg, Germany, 2013. [CrossRef]
49. Cullity, B.D.; Graham, C.D. *Introduction to Magnetic Materials*; Wiley: Hoboken, NJ, USA, 2008. [CrossRef]
50. Karpel, S. Permanent Magnets. *Metal Bulletin Monthly*, August 2005; 42–43.
51. German, R. *Sintering: From Empirical Observations to Scientific Principles*; Elsevier: Oxford, UK, USA, 2014. [CrossRef]
52. Honshima, M.; Ohashi, K. High-Energy NdFeB Magnets and their Applications. *J. Mater. Eng. Perform.* **1994**, *3*, 218–222. [CrossRef]
53. Luo, J.; de Rango, P.; Fruchart, D.; Mei, J.; Zhou, L. Hydrogen Absorption and Desorption Characteristics of High Coercivity NdDyFeCoNbCuB Sintered Magnet. I. Low Temperature Hydrogen Decrepitation Treatments. *J. Alloys Compd.* **2011**, *509*, 4252–4259. [CrossRef]
54. Srekl, M.; Bratina, B.; Zagirnyak, M.; Benedicic, B.; Miljavec, D.; Demenko, A. Losses in the Axial-Flux Permanent Magnet Machine Housing. *Compel* **2013**, *32*, 1366–1382. [CrossRef]
55. Balachandran, A.; Boden, M.; Sun, Z.; Forrest, S.; Ede, J.; Jewell, G.W. Design, Construction, and Testing of an Aero-Engine Starter-Generator for the More-Electric Aircraft. *J. Eng.* **2019**, *2019*, 3474–3478. [CrossRef]
56. Linquip. What Is a Motor Shaft? 31 August 2021. Available online: https://www.linquip.com/blog/what-is-motor-shaft/ (accessed on 11 January 2022).
57. Nisbett, E.G. Chapter 5: Types of Forging. In *Steel Forgings: Design, Production, Selection, Testing and Application*; ASTM International: West Conshohocken, PA, USA, 2005; pp. 24–31.
58. Jaczczolt, C. Understanding Permanent Magnet Motors. 31 January 2017. Available online: https://www.controleng.com/articles/understanding-permanent-magnet-motors/ (accessed on 11 January 2022).
59. Yon, J.M.; Mellor, P.H.; Wrobel, R.; Booker, J.D.; Burrow, S.G. Analysis of Semipermeable Containment Sleeve Technology for High-Speed Permanent Magnet Machines. *IEEE Trans. Energy Convers.* **2012**, *27*, 646–653. [CrossRef]
60. Zhang, F.; Du, G.; Wang, T.; Liu, G.; Cao, W. Rotor Retaining Sleeve Design for a 1.12-ML High Speed PM Machine. *IEEE Trans. Ind. Appl.* **2015**, *51*, 3675. [CrossRef]
61. Gallo, M.; Moreschi, L.; Borghi, A.D. A Critical Environmental Analysis of Strategic Materials towards Energy Transition. *Detritus Multidiscip. J. Waste Resour. Residues* **2022**, *20*, 3–12. [CrossRef]
62. National Research Council (US) Chemical Sciences Roundtable. *The Role of the Chemical Sciences in Finding Alternatives to Critical Resources: A Workshop Summary*; National Academies Press: Washington, DC, USA, 2012. [CrossRef]
63. European Chemical Society. The Periodic Table and Us: It's History, Meaning and Element Scarcity. 2019. Available online: https://www.euchems.eu/periodic-table-and-us/ (accessed on 13 January 2022).
64. Centre for Sustainable Systems, University of Michigan Critical Materials Factsheet. 2021. Available online: https://css.umich.edu/publications/factsheets/material-resources/critical-materials-factsheet (accessed on 15 March 2024).
65. Hayes, S.M.; McCullough, E.A. Critical Minerals: A Review of Elemental Trends in Comprehensive Criticality Studies. *Resour. Policy* **2018**, *59*, 192–199. [CrossRef]

66. Emil, E.; Kaya, O.; Stopić, S.; Gurmen, S.; Friedrich, B. NdFeB Magnets Recycling Process: An Alternative Method to Produce Mixed Rare Earth Oxide from Scrap NdFeB Magnets. *Metall. J.* **2021**, *11*, 716. [CrossRef]
67. Kopeliovich, D. Carbon Steel SAE 1045. 2012. Available online: http://substech.com/dokuwiki/doku.php?id=carbon_steel_sae_1045 (accessed on 11 January 2022).
68. AZO Materials Nickel Alloy Inconel 718—Properties and Applications by United Performance Metals. 14 November 2008. Available online: https://www.azom.com/article.aspx?ArticleID=4459 (accessed on 11 January 2022).
69. Dorian, J.P.; Humphreys, H.B. *Economic Impacts of Mining: A Changing Role in the Transitional Economies*; Wiley: Hoboken, NJ, USA, 1994. [CrossRef]
70. Ericsson, M.; Löf, O. Mining's Contribution to National Economies between 1996 and 2016. *Miner. Econ.* **2019**, *32*, 223–250. [CrossRef]
71. Azadeh, A.; Osanloo, M.; Ataei, M. A New Approach to Mining Method Selection Based on Modifying the Nicholas Technique. *Appl. Soft Comput. J.* **2010**, *10*, 1040–1061. [CrossRef]
72. Simmons + Simmons Financing Sustainability in the Mining Sector. 2019. Available online: https://www.simmons-simmons.com/en/publications/ck2nkylht5z630b12l59wq41z/financing-sustainability-in-the-mining-sector (accessed on 1 June 2023).
73. Robertson, S.; Blackwell, B. Mine Lifecycle Planning and Enduring Value for Remote Communities. *Int. J. Rural. Law Policy* **2014**, *1*, 1–11. [CrossRef]
74. EPA Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues. *US EPA Reg.* **2012**, *8*, 189–200.
75. AGI. What are Environmental Regulations on Mining Activities. Available online: https://www.americangeosciences.org/critical-issues/faq/what-are-regulations-mining-activities (accessed on 17 January 2022).
76. Jain, R.K.; Cui, Z.; Domen, J.K. Chapter 3—Environmental Management System Implementation in the Mining Industry. In *Environmental Impact of Mining and Mineral Processing*; Elsevier: Oxford, UK, 2016; pp. 35–52. [CrossRef]
77. Somarin, A. *Mining and the Environment: What Happens When a Mine Closes?* ThermoFisher Scientific: Waltham, MA, USA, 2014.
78. Onwe, R.; Abraham, E. Environmental Problems of Surface and Underground Mining: A Review. *Int. J. Eng. Sci.* **2015**, *4*, 12–20.
79. Espinoza, D.; Goycoolea, M.; Moreno, E.; Newman, A. MineLib: A Library of Open Pit Mining Problems. *Ann. Oper. Res.* **2013**, *206*, 93–114. [CrossRef]
80. Seredkin, M.; Zabolotsky, A.; Jeffress, G. In Situ Recovery, an Alternative to Conventional Methods of Mining: Exploration, Resource Estimation, Environmental Issues, Project Evaluation and Economics. *Ore Geol. Rev.* **2016**, *79*, 500–514. [CrossRef]
81. Jha, M.K.; Kumari, A.; Panda, R.; Kumar, J.R.; Yoo, K.; Lee, J.Y. Review on Hydrometallurgical Recovery of Rare Earth Metals. *Hydrometallurgy* **2016**, *161*, 77. [CrossRef]
82. Kidela Capital Group Rare Earth Processing 101. 2011. Available online: https://www.kitco.com/ind/Kidela/may102011.html (accessed on 25 July 2021).
83. Massachusetts Institute of Technology Green Refinement. Available online: https://web.mit.edu/12.000/www/m2016/finalwebsite/solutions/greenrefining.html (accessed on 25 July 2021).
84. Yu, J.; Han, Y.; Li, Y.; Gao, P. Recent Advances in Magnetization Roasting of Refractory Iron Ores: A Technological Review in the Past Decade. *Miner. Process. Extr. Metall. Rev.* **2019**, *41*, 349. [CrossRef]
85. Pecharky, V.K.; Gschneidner, K.A., Jr. *Rare Earth Element*; Encyclopedia Britannica: London, UK, 2019.
86. Whitworth, A.J.; Forbes, E.; Verster, I.; Jokovic, V.; Awatey, B.; Parbhakar-Fox, A. Review on advances in mineral processing technologies suitable for critical metal recovery from mining and processing wastes. *Clean. Eng. Technol.* **2022**, *7*, 100451. [CrossRef]
87. European Commission Mining Waste. Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/mining-waste_en#:~:text=Tailings%20are%20often%20stored%20in,the%20economy%20and%20the%20environment (accessed on 21 February 2023).
88. EcoCycle. How Is Mining Waste Recycled? 2016. Available online: https://ecocycle.com.au/blog/how-is-mining-waste-recycled/ (accessed on 23 February 2023).
89. Recycle-More Steel. Available online: https://www.recycle-more.co.uk/what-can-i-recycle/steel#:~:text=Recycling%20Steel%20Saves%20Energy%20and%20Reduces%20Pollution&text=The%20use%20of%20scrap%20steel,1.5%20tonnes%20of%20iron%20ore (accessed on 23 February 2023).
90. Liu, J.; Walmer, M. Process and Magnetic Properties of Rare-Earth Bonded Magnets. In *Handbook of Advanced Magnetic Materials*; Springer: Berlin/Heidelberg, Germany, 2006; pp. 1008–1044. [CrossRef]
91. Yan, G.H.; Chen, R.J.; Ding, Y.; Guo, S.; Lee, D.; Yan, A.R. The Preparation of Sintered NdFeB Magnet with High-Coercivity and High Temperature-Stability. *J. Phys. Conf. Ser.* **2011**, *266*, 012052. [CrossRef]
92. Zakotnik, M.; Tudor, C.O.; Peiró, L.T.; Afiuny, P.; Skomski, R.; Hatch, G.P. Analysis of Energy Usage in Nd–Fe–B Magnet to Magnet Recycling. *Environ. Technol. Innov.* **2016**, *5*, 117–126. [CrossRef]
93. Fruchart, D.; Bacmann, M.; de Rango, P.; Isnard, O.; Liesert, S.; Miraglia, S. Hydrogen in Hard Magnetic Materials. *J. Alloys Compd.* **1997**, *253*, 121–127. [CrossRef]
94. Kianvash, A.; Harris, I.R. The Production of a Nd 16Fe 76B 8 Sintered Magnet by the Hydrogen Decrepitation/Hydrogen Vibration Milling Route. *J. Alloys Compd.* **1999**, *282*, 213–219. [CrossRef]

95. Akhtar, S.; Haider, A.; Ahmad, Z.; Farooque, M. Development of NdFeB Magnet through Hydrogen Decrepitation. *Key Eng. Mater.* **2010**, *442*, 263–267. [CrossRef]
96. Takeshita, T.; Morimoto, K. Anisotropic Nd–Fe–B Bonded Magnets Made from HDDR Powders. *J. Appl. Phys.* **1996**, *79*, 5040–5044. [CrossRef]
97. Takeshita, T. Some Applications of Hydrogenation-Decomposition-Desorption-Recombination (HDDR) and Hydrogen-Decrepitation (HD) in Metals Processing. *J. Alloys Compd.* **1995**, *231*, 51–59. [CrossRef]
98. Sprecher, B.; Xiao, Y.; Walton, A.; Speight, J.; Harris, R.; Kleijn, R. Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets. *Environ. Sci. Technol.* **2014**, *48*, 3951–3958. [CrossRef]
99. Sagawa, M.; Nagata, H.; Watanabe, T.; Itatani, O. Rubber Isostatic Pressing (RIP) of Powders for Magnets and Other Materials. *Mater. Des.* **2000**, *21*, 243–249. [CrossRef]
100. Bunting E-Magnets. How Magnets Are Made. Available online: https://e-magnetsuk.com/introduction-to-neodymium-magnets/how-neodymium-magnets-are-made/ (accessed on 23 July 2021).
101. Popov, A.G.; Golovnia, O.A.; Bykov, V.A. Pressless Process in Route of Obtaining Sintered Nd–Fe–B Magnets. *J. Magn. Magn. Mater.* **2015**, *383*, 226–231. [CrossRef]
102. Cheng, C.W.; Cheng, F.T.; Man, H.C. Improvement of Protective Coating on Nd–Fe–B Magnet by Pulse Nickel Plating. *J. Appl. Phys.* **1998**, *83*, 6417–6419. [CrossRef]
103. Man, H.H.; Man, H.C.; Leung, L.K. Corrosion Protection of NdFeB Magnets by Surface Coatings—Part 2: Electrochemical Behaviour in Various Solutions. *J. Magn. Magn. Mater.* **1996**, *152*, 47–53. [CrossRef]
104. Coelho, F.; Abrahami, S.; Yang, Y.; Sprecher, B.; Li, Z.; Menad, N.-E.; Bru, K.; Marcon, T.; Rado, C.; Saje, B.; et al. Uppscaling of Permanent Magnet Dismantling and Recycling through VALOMAG Project. In Proceedings of the International Conference on Raw Materials and Circular Economy, Athens, Greece, 5–9 September 2021. [CrossRef]
105. Wrobel, R.; Mecrow, B. Additive Manufacturing in Construction of Electrical Machines—A Review. In Proceedings of the IEEE Workshop on Elelctrical Machines Design, Control and Diagnosis (WEMDCD), Athens, Greece, 22–23 April 2019; pp. 15–22. [CrossRef]
106. Högberg, S.; Pedersen, T.S.; Bendixen, F.B.; Mijatovic, N.; Jensen, B.B.; Holboll, J. Direct Reuse of Rare Earth Permanent Magnets—Wind Turbine Generator Case Study. In Proceedings of the XXII International Conference on Electrical Machines, Lausanne, Switzerland, 4–7 September 2016.
107. Pavel, C.C.; Lacal-Arantegui, R.; Marmier, A.; Schüler, D.; Tzimas, E.; Buchert, M.; Jenseit, W.; Blagoeva, D. Substitution Strategies for Reducing the use of Rare Earths in Wind Turbines. *Resour. Policy* **2017**, *52*, 349–357. [CrossRef]
108. Davenport, W.G.; King, M.; Schlesinger, M.; Biswas, A.K. Chapter 22—Melting and Casting. In *Extractive Metallurgy of Copper*; Elsevier: Amsterdam, The Netherlands, 2002; pp. 367–383. [CrossRef]
109. Robinson, J.; Munagala, S.; Arjunan, A.; Simpson, N.; Jones, R.; Baroutaji, A.; Govindaraman, L.T.; Lyall, I. Electrical Conductivity of Additively Manufactured Copper and Silver for Electrical Winding Applications. *Materials* **2022**, *15*, 7563. [CrossRef]
110. Lina Hot Rolled Steel vs. Cold Rolled Steel—What's the Difference? 2019. Available online: https://www.steelo.co.uk/blog/2019/03/26/hot-vs-cold-rolled-steel-whats-difference/ (accessed on 24 September 2021).
111. Xia, C.; Wang, H.; Wu, Y.; Wang, H. Joining of the Laminated Electrical Steels in Motor Manufacturing: A Review. *Materials* **2020**, *13*, 20. [CrossRef] [PubMed]
112. Parker, F. Chapter 28—Alternating Current Generators. In *Electrical Engineer's Reference Book*; Elsevier: Oxford, UK, 2003; ISBN 9780080523545.
113. Billur, E. *Hot Stamping of Ultra High-Strength Steels*; Springer: Cham, Switzerland, 2019. [CrossRef]
114. Zhan, M.; Sun, Z.; Yang, H. Modeling of Hot Forging. *Mater. Sci. Mater. Eng.* **2014**, *5*, 441–493.
115. Behrens, B.A.; Bouguecha; Lüken, I.; Mielke, J.; Bistron, M. Tribology in Hot Forging. *Mater. Sci. Mater. Eng.* **2014**, *5*, 211–234.
116. Eurofer Circular Economy. 27 March 2020. Available online: https://www.eurofer.eu/issues/environment/circular-economy/#:~:text=56%25%20of%20EU%20steel%20is,truly%20circular%20economy%20in%20Europe (accessed on 1 June 2023).
117. Berns, H.; Theisen, W. *Ferrous Materials: Steel and Cast Iron*; Springer: Leipzig, Germany, 2008. [CrossRef]
118. Sizek, H.W. Radial Forging. In *Metalworking*; ASM International: Bulk Forming, OH, USA, 2005; pp. 172–178.
119. Lynco. What You Need to Know about Forged Steel Pipe Fittings. 27 November 2019. Available online: https://lyncoflange.com/what-you-need-to-know-about-forged-steel-pipe-fittings/ (accessed on 17 March 2022).
120. SMMT. *2021 UK Automotive Sustainability Report*; SMMT: London, UK, 2021.
121. *TERM Electric Vehicles from Life Cycle and Circular Economy Perspectives*; European Environment Agency: Copenhagen, Denmark, 2018.
122. Ingram, E. How to Extend the Lifetime of Wind Turbines. 2019. Available online: https://www.renewableenergyworld.com/om/how-to-extend-the-lifetime-of-wind-turbines/#gref (accessed on 26 September 2021).
123. Bianchi, N.; Bolognani, S.; Frare, P. Design Criteria for High-Efficiency SPM Synchronous Motors. *IEEE Trans. Energy Convers.* **2006**, *21*, 396–404. [CrossRef]
124. Acorn ISL. 5 Ways to Improve the Efficiency of your Electric Motor. 2019. Available online: https://www.acorn-ind.co.uk/insight/5-ways-to-improve-the-efficiency-of-your-electric-motor/ (accessed on 17 January 2022).
125. Csanyi, E. Five Factors That Mess Up Motor Efficiency and How to Improve It. 2015. Available online: https://electrical-engineering-portal.com/5-factors-that-mess-up-motor-efficiency-and-how-to-improve-it (accessed on 17 January 2022).

126. Staffell, I.; Green, R. How does Wind Farm Performance Decline with Age? *Renew. Energy* **2014**, *66*, 775–786. [CrossRef]
127. Kuran, M. Predictive Maintenance: How Sensors Monitor Wind Turbines in Real Time. 2019. Available online: https://www.power-and-beyond.com/predictive-maintenance-how-sensors-monitor-wind-turbines-in-real-time-a-885000/ (accessed on 8 March 2022).
128. HSE Waste Electrical and Electronic Equipment Recycling (WEEE). 2020. Available online: https://www.hse.gov.uk/waste/waste-electrical.htm (accessed on 17 January 2022).
129. Nordelöf, A.; Grunditz, E.; Lundmark, S.; Tillman, A.-M.; Alatalo, M.; Thiringer, T. Life Cycle Assessment of Permanent Magnet Electric Traction Motors. *Transp. Res. Part D Transp. Environ.* **2019**, *67*, 263–274. [CrossRef]
130. Francis, S. The State of Recycled Carbon Fiber. 2019. Available online: https://www.compositesworld.com/articles/the-state-of-recycled-carbon-fiber (accessed on 8 March 2022).
131. Binnemans, K.; Jones, P.T.; Blanpain, B.; Van Gerven, T.; Yang, Y.; Walton, A.; Buchert, M. Recycling of Rare Earths: A Critical Review. *J. Clean. Prod.* **2013**, *51*, 1–22. [CrossRef]
132. Elwert, T.; Goldmann, D.; Römer, F.; Buchert, M.; Merz, C.; Schueler, D.; Sutter, J. Current Developments and Challenges in the Recycling of Key Compnents of (Hybrid) Electric Vehicles. *Recycling* **2015**, *1*, 25–60. [CrossRef]
133. Walton, A.; Yi, H.; Rowson, N.A.; Speight, J.D.; Mann, V.D.J.; Sheridan, R.S.; Bradshaw, A.; Harris, I.R.; Williams, A.J. The use of Hydrogen to Separate and Recycle Neodymium-Iron-Boron Type Magnets from Electronic Waste. *J. Clean. Prod.* **2015**, *104*, 236–241. [CrossRef]
134. Zakotnik, M.; Tudor, C.O. Commercial Scale Recyling of NdFeB Type Magnets with Grain Boundary Modification Yields Products with Designer Properties that Exceed those of Starting Materials. *J. Waste Manag.* **2015**, *44*, 48–54. [CrossRef]
135. Bové, A.-T.; Swartz, S. Starting at the Source: Sustainability in Supply Chains. 2016. Available online: https://www.mckinsey.com/business-functions/sustainability/our-insights/starting-at-the-source-sustainability-in-supply-chains (accessed on 2 October 2021).