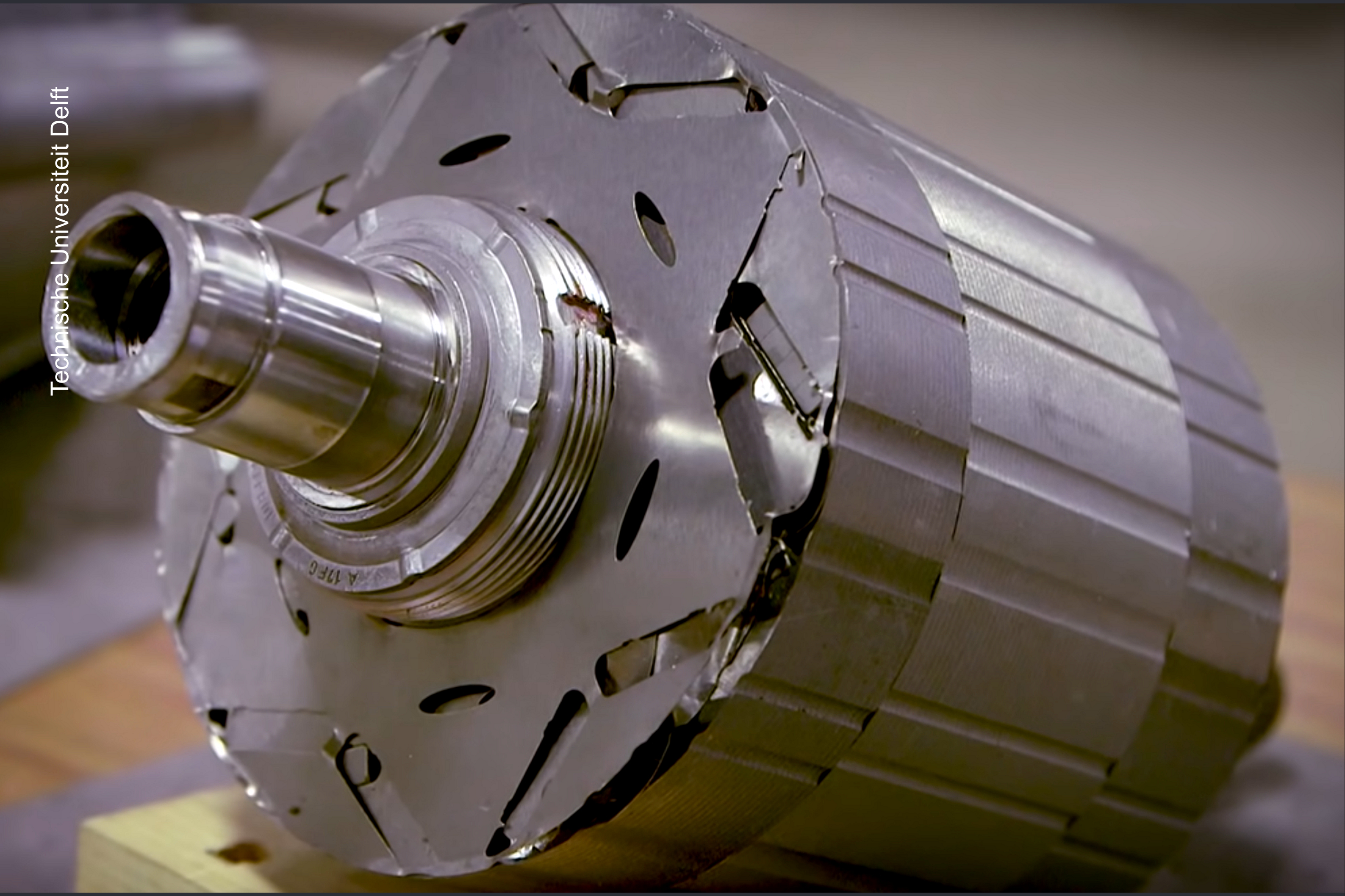
Circularity of Critical Raw Materials in Electric Aviation

R.J. Joensuu



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The cover image shows an internal permanent magnet synchronous reluctance motor from a Tesla Model 3. Photo by Bloomberg.

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by

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Preface

Six years ago I moved to the Netherlands to follow a dream: to study Aerospace Engineering. Now, as I am about to graduate from the MSc programme, this period of my life is coming to an end. It is time for new dreams. I have definitely learned a lot in the past six years - not only about aircraft, but also about myself. One of the best experiences in my academic journey was definitely the Design Synthesis Exercise (or more familiarly the DSE), which concluded the BSc programme. Our team managed to design an aircraft that was (supposed to be) sustainable and circular, the CESTREL. This project actually inspired me to continue my studies in the field of materials, with a focus on sustainability and circularity.

Eventually, I ended up working on this thesis and the topic of critical raw materials. The topic is like a black hole - once you are in, you cannot escape. There are so many aspects to critical raw materials that it becomes quite challenging to limit yourself and to set some boundaries to the research project. At the same time, it is extremely interesting. We are so dependent on these materials without even realizing it. Good luck to all students working on the topic of critical raw materials in the future!

A year ago I could not imagine that I would actually finish my thesis and graduate one day. It has been a difficult year and a bit for me personally, and I am proud to have finally made it this far. I am thankful to all the people who have been there to support me. Timo, I would not have managed to finish this thesis without you, you have been a great thesis buddy. Kristie, Aïcha, Katha, I am so grateful to have you in my life, I can always rely on you. To all of my amazing friends who have made the past year much more fun: your friendship means a lot to me. I would like to thank my supervisors Irene and David for their patience and guidance. A special recognition also goes to my colleagues at work, who have seen me lead a double life - part student, part working employee. You have shown your support at work, and offered me flexibility to get this thesis done. I also want to thank my mom for her wise words and support.

Thank you Liam for believing in me more than I ever did.

Abstract

Components of novel propulsion systems in electric aviation contain materials defined as critical by the European Union: electric motors contain Rare Earth Elements neodymium and dysprosium, and state-of-the-art batteries materials like lithium and cobalt. Such critical raw materials have high supply risks but are crucial for the economy. The demand of all these materials is forecasted to increase drastically in the coming years, which means that the rate of supply might no longer suffice to fill the demand. Circular economy principles have been suggested as a solution. Materials recovered from end-of-life components can secure supplies and reduce the environmental impact of products.

In this research, the implementation of circular economy approaches to address critical raw material demand in electric aviation is studied. According to the developed models, the material demand is negligible in comparison to other industries until 2050. However, as the electric aircraft technologies are still in development, there is a lot of uncertainty around the demand.

Beyond 2050, components will start reaching their end-of-life stage. In this case, a circular strategy considered feasible for electric motors is remanufacturing. After the Rare Earth Element magnets in the motors become obsolete, they can be recycled to recover the critical raw materials. Both hydrogen decrepitation and a combination of hydro- and pyrometallurgical processes can be used to regain materials for magnets in aviation or other applications.

Although circular economy strategies will not be able to significantly reduce the primary material demand in electric aviation by 2050, these can still lower the environmental impacts from production. Additionally, well-established circular practices could address the material demand more substantially in the future, after 2050, if electric technologies are more widely adopted then.

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Introduction

The effects of human-induced global warming are becoming increasingly apparent. Various policies are being implemented to accelerate the energy transition to renewables and to stimulate electrification. The aviation industry also has to convert to alternative, sustainable fuels in order to mitigate its environmental impacts [1, 5]. Currently, the aviation sector is responsible for approximately 2-3% of the global CO2 emissions [1, 50]. Additionally, aircraft also have non-CO2 emissions, such as water vapor and nitrogen oxides, which further contribute to global warming [50].

Various sustainable fuels and means of propulsion exist - from combustion of sustainable aviation fuel to flying on hydrogen fuel cells [1, 5, 50]. Novel propulsion system configurations use electric power, in which case batteries or fuel cells can be used for power generation, and electric motors rotate the fans or propellers [29]. Flying purely on batteries and electric power means that in-flight CO2 and non-CO2 emissions are completely eliminated [29, 69]. However, electrification in aviation has its limitations: due to lower energy densities, such electric energy sources are only feasible for smaller aircraft [66, 69].

Electrification introduces new components and materials, such as electric motors, batteries, and fuel cells, into the aviation sector. All of these components are widely used in other economically important sectors, such as renewable energy and electric transport in general [12]. The components contain critical raw materials (CRM) - materials with high supply risks that are crucial to the economy [10, 12]. Electric motors contain Rare Earth Elements (REEs), such as neodymium (Nd) and dysprosium (Dy) and batteries include lithium (Li) and cobalt (Co) [10, 12]. Critical raw materials are not often discussed in the context of commercial aviation, especially regarding novel technologies that are still in development.

The European Union's (EU) assessment of material criticality considers over 60 raw materials, out of which 30 are labelled as critical [10]. In case of REEs, the EU is fully dependent on material imports [10]. Over 80% of the cobalt and all 100% of the lithium used within the Union are also imported [10]. All of these materials are crucial in a variety of applications: from batteries, motors to electronics [12]. Supply issues could have severe consequences on the development and implementation of energy systems and electric technologies [12]. The EU has recognised the importance of critical raw materials to the economy and has therefore prepared a regulatory proposal for ensuring their supply, known as the Critical Raw Materials Act [23].

Circular economy strategies have been suggested as a solution to ensure supplies of critical raw materials, reducing the dependence on material imports [23, 26, 28, 77]. The Critical Raw Materials Act proposes that at least 15% of the annual consumption of strategic materials (including lithium, cobalt and REEs) should come from recycled secondary materials [23]. In a linear economy, materials are extracted, manufactured into products, used and then discarded. A circular economy aims to minimize waste. Instead, materials and products loop back into the economy after they reach their end-of-life stage. The end-of-life strategies of a circular economy include reuse, remanufacture and recycle [2, 3, 26]. In general, reusing, remanufacturing and recycling processes have lower emissions and energy use compared to primary production [2, 3]. The optimal route for a specific product can be chosen based on minimizing the environmental impact.

Yet, the increasing complexity and the requirements of engineering products make it challenging to implement circular end-of-life strategies [7]. Circular strategies are not well-studied for the aviation sector, especially considering novel technologies and materials that come with them. However, they should be considered for multiple reasons: firstly, production of components, such as electric motors and batteries, is energy-intensive [61, 69]. Secondly, these components contain critical raw materials. As the future demand for these materials is expected to increase across all sectors, it is uncertain how the demand of the aviation sector and other sectors will be met in the future. Thirdly, circularity should be considered at an early design stage in order to incorporate it into the product [7, 65].

This research aims to bridge the gaps between electric aviation, critical raw materials and circularity. The objective is to investigate how circular economy strategies can be implemented for critical raw materials in electric aviation. As the electric aviation technologies are still in development, research on this topic is timely. Components studied here are electric motors and batteries, and the specific materials looked into are REEs neodymium and dysprosium, and lithium and cobalt. The research will investigate the material demand from these components in aviation and then focus on circular strategies for them.

First, in Chapter 2 the literature studied around the topics of critical raw materials, electric aviation and circularity is summarized. Based on the findings of the literature study, the research scope and objective are refined and presented in Chapter 3. The first part of the research, material demand prediction, is explained in Chapter 4. Here everything from data collection, methodology and results are discussed. This is followed by the second part of the research, circular strategies, in Chapter 5. Finally, the research and the recommendations are summarized in Chapter 6.

2

Literature review

In this Chapter the studied literature and the identified research gaps are presented. First, the three main areas of research are introduced: material criticality, electric aviation and circularity. After this, the environmental impacts of components in electric aviation are discussed, and possible end-of-life strategies reviewed on a high level. Lastly, essential information on magnetic materials is presented to provide background knowledge for the research.

2.1. Critical raw materials

The concept of criticality refers to non-fuel material resources that important to the economy but have high supply risks [3, 10, 71]. Global economies depend on access to raw materials, yet most countries have to import material resources from elsewhere. Economic growth and technological development are raising the resource demand [3, 7, 77], which is expected to surpass production rates for some materials in the near future [12]. The concept of criticality was thus developed to described materials where there is a risk of supplies not meeting the demand [2, 3, 71].

As challenges in supply and demand depend on geographical location and geopolitics, the lists of critical raw materials differ across the globe [71]. The European Union (EU) defines criticality based on two parameters: the economic importance and the supply risk of the material [10]. The 2020 assessment includes 63 individual and three grouped materials, with 30 materials being identified as critical [10]. For many critical raw materials, the EU fully relies on imports [10]. The results of the assessment are presented in Figure 2.1, showing the supply risk and the economic importance of materials, and the thresholds for criticality. Critical raw materials include for example lithium, cobalt and the Rare Earth Element (REE) group, which are all materials crucial for renewable energy and electrification [12].

Within the EU, the focus is on materials for strategic sectors, such as energy, e-mobility, and defense sectors [12]. The EU forecast indicates that material demand for just electric vehicles and renewable energy will exceed current demand from all sectors and applications [12], which will leave the production vulnerable to the supplies of these materials. Circular economy practices could lower supply risks and ensure sufficient material supplies [28, 77].

Two research gaps have been identified. Firstly, the author found that while the discussion on critical raw materials is looking into new technologies, especially in electric mobility, the aviation sector is not often considered. Like many other industries, aviation is shifting to new more sustainable practices by means of new fuels and propulsion systems. These require new components and materials, some of which are critical.

Secondly, the EU assessment of raw materials lacks information on material flows and quantities into parts and products. The applications of a material need to be examined in further detail in order to evaluate the feasibility of circular economy strategies, and how they relate to the supply and demand.

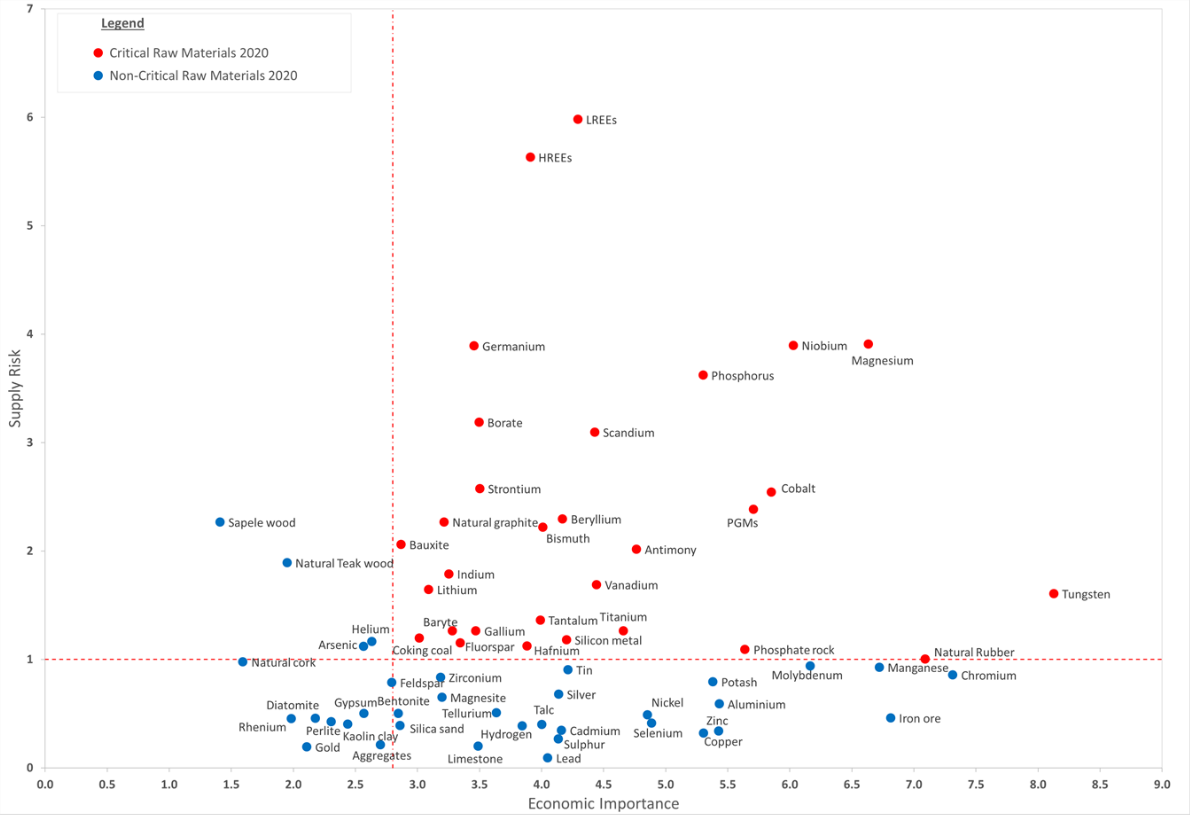

Figure 2.1: Results of the EU's critical raw material assessment of 2020 [10]. Materials are plotted based on their calculated economic importance (x-axis) and their supply risk (y-axis). For further information on criticality assessment and the calculation method, the reader is referred to the EU study of critical raw materials [10].

2.2. Electric aviation configurations and components

The aviation industry needs critical raw materials for the development of more environmentally friendly propulsion systems. Different propulsion system configurations for aircraft include electric or gas turbine power generation with fuel, batteries, or capacitors as the energy source [29]. These are visually presented in Figure 2.2. For this study, interesting propulsion systems are ones that include electric power transmissions, as these introduce new components and critical raw materials to the sector. Capacitors are not considered. The technologies are presented in the list below.

- **Battery-electric** propulsion is the most sustainable option in operation, eliminating in-flight emissions [29, 69]. However, current state-of-the-art lithium-ion batteries can only reach energy densities of 250 Wh/kg, whereas kerosene has an energy density of 12,000 Wh/kg [66, 69]. Batteries with higher energy densities are required in order to make battery-electric flights commercially feasible and attainable for larger aircraft [66, 69].

- **Hybrid** configurations that combine a gas turbine with a battery can also achieve emission reductions [29]. These are divided into four categories: series, parallel, series-parallel, and turbo-electric [66, 93].

- **Hydrogen** combustion or fuel cells can also be used for propulsion in aircraft. Electric

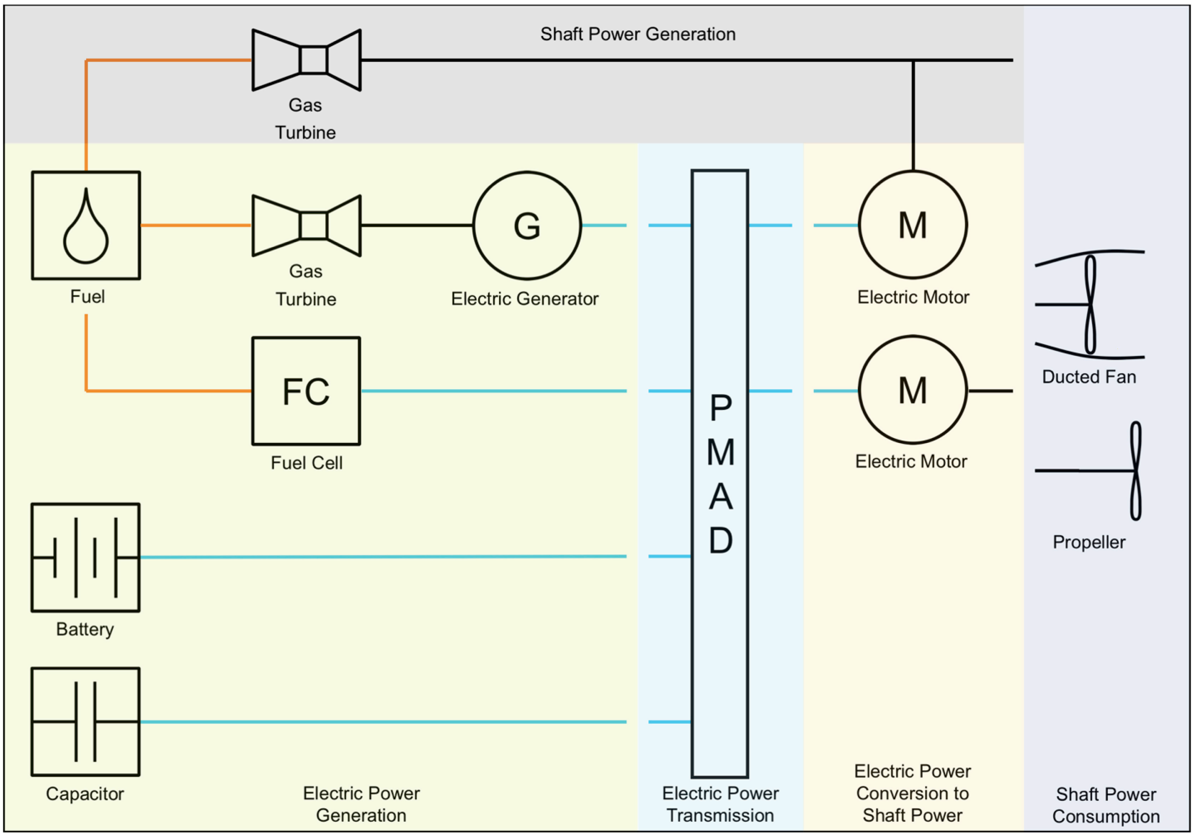

Figure 2.2: Schematic of propulsion system configurations for aircraft from Gnadt et al. [29] (adapted from original, Pornet et al. [62]).

motors rotate the fans in a fuel cell configuration [50]. In order to gain more energy storage, batteries could be installed to a fuel cell hydrogen aircraft [50].

Battery-electric, hybrid and fuel cell aircraft are all seen as electric aircraft, since they include electric motors in their propulsion systems. Additionally, battery-electric and hybrid aircraft contain batteries as an energy source.

High specific power is required from electric motors in the aviation industry [29, 93]. Permanent magnet motors are the most feasible current option due to their high specific power and commercial availability [22, 29, 66]. Lithium-ion batteries are the chosen battery chemistry for aviation, since they have the highest energy density [66, 69]. Lithium-sulfur and lithium-air compositions could reach even higher energy densities in the future [66, 67].

The permanent magnet motors appropriate for use in aircraft applications include magnets out with a Neodymium-Iron-Boron (NdFeB) composition [9, 66]. The magnets contain Rare Earth Elements (REEs), namely neodymium and dysprosium, which are critical raw materials in the EU [10]. Both are imported to the EU from China. Lithium-ion batteries contain both lithium and cobalt, also critical raw materials in EU.

2.3. Circularity of products and materials

Currently, materials are used in a linear economy, where materials as treated as consumables. Materials are extracted, manufactured, used, and then discarded as waste. Raw material extraction and processing are energy-intensive and polluting activities [2, 3]. In such a linear economy, resources are used inefficiently and the approach has negative environmental impacts [2, 3]. Additionally, global growth has led to an overuse of resources [3]. The concept of circular economy proposes that the environmental burden and waste generation can be minimized by rethinking resource use [2, 3]: materials could be used in multiple cycles and potentially in changing functions, rather than be seen as consumables.

A circular economy approach is inspired by the self-sustaining character of natural ecosystems [2, 3]. Figure 2.3, as proposed by the U.S. Chamber of Commerce Foundation [1], illustrates principles of a circular economy on finite materials. The approach aims to extend material deployment within industrial ecosystems but also to support sustainable development [2, 3]. A circular economy intends to reduce the impact of energy-intensive and polluting material extraction and manufacturing activities. Therefore, the first strategies to consider are ’Rethink and Reduce’ and ’Redesign’, as shown in Figure 2.3, both with the goal of lowering material consumption. Other circular economy strategies can be implemented to loop materials back into the use cycle at different stages. The final one, ’Recover’, refers to incinerating materials for energy recovery.

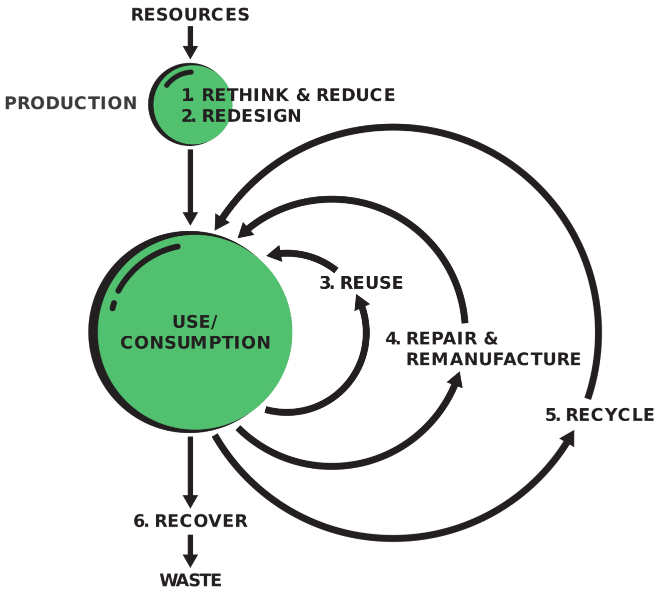

Figure 2.3: Circular economy strategies for finite raw materials, from U.S. Chamber of Commerce Foundation.

The following definitions for circular strategies are used, based on the framework developed by Blomsma and Tennant [11] and the definitions from Ashby [2, 3] and Gaustad et al. [26]:

- **Reuse**: end-of-life products are reused as-is in the same use application.
- **Repurpose**: end-of-life product is redistributed as-is to a different use application.
- **Repair**: product life extension through repairing of parts.

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[1] https://www.uschamberfoundation.org/file/linear-vs-circular-economy-diagram-plant-chicagopng

- **Remanufacturing**: end-of-life product life extension through repairing of parts such that product performance and quality are returned to an equivalent or better state than that of the original.

- **Recycling**: materials of a product are processed to recover individual elements or mixed materials for further manufacturing of parts.

Circular economy strategies can also be applied to critical raw materials in order to secure supplies and reduce the criticality of such materials [26, 28, 77]. The EU assessment methodology takes into account the end-of-life recycling input rate, thus the input of recycled material into the supply chain [10]. It leads to reduced demand of primary (imported) materials and therefore lower supply risks [10]. However, currently, most critical raw materials have low recycling rates [7, 10, 26]. In the future, it is expected that recycling could become increasingly important in supplying critical raw materials [22, 26, 79]. Recycling of critical raw materials is also supported by EU policy, which might even mandate future recycling rates to ensure material supplies to the economy [23]. According to the current regulatory proposal, recycled secondary materials should account for at least 15% of the annual use of so called strategic materials, which include lithium, cobalt, and REEs [23].

Other circular economy strategies can help also address the supply risk of critical raw materials [7, 16, 26, 39]: product reuse, lifetime extension through repair and remanufacturing can also reduce the demand of primary materials. Research on critical raw materials has centred around recycling and has often ignored other circular economy strategies [16, 26]. One reason is that in engineering applications, the end-of-life stage of a product is rarely considered in the design [7]. It has been suggested that the applicable circular strategies for critical raw materials should be looked into on a product level, as done in a study by Cimprich et al. [16] and supported by the conclusions of Gaustad et al. [26]. The Resource States Framework developed by Blomsma and Tennant [11] can be applied to investigate the feasibility of different strategies.

2.4. Environmental impact of electric components

Life cycle assessment (LCA) tracks the various stages in a product's life, from raw materials extraction, manufacturing, use, to end-of-life [3]. Through an LCA, it is possible to quantify the resources used and the environmental impacts at each stage [3]. Although LCA is a time-consuming process, it can provide valuable information for making design choices that are better for the environment.

The environmental impact of electric aviation is still an upcoming research topic. So far research shows that the use stage, operation of the aircraft, has the highest environmental impact due to the energy consumption in terms of electricity [29, 61, 67, 69]. The total environmental impact of an electric aircraft highly depends on the electricity source and thus the share of renewables in the electricity mix [29, 61, 67, 69]. The researchers Melo et al. concluded that even though some environmental assessments exist for electric aviation, there is a gap in research considering the use of critical raw materials in such aircraft configurations [61].

Electric aircraft have a higher share of emissions from the manufacturing stage than kerosene aircraft [61, 69]. The environmental impact of the manufacturing phase of electric aircraft is increased by the energy-intensive battery production [29, 69]. Battery production is estimated to contribute between 2-12% of the lifecycle emissions of an all-electric aircraft [29, 69]. The results vary, as different assumptions are made with respect to the battery type, composition, energy density and operational parameters.

The cathode material influences the energy consumption and emissions during battery production the most. Studies have compared the environmental impacts of potential battery solutions for electric aircraft [8, 51]. According to these, the lithium-sulfur battery (LSB) is the most attractive solution in terms of lowest environmental impact [8, 51]. However, further research into the end-of-life strategies for batteries in aviation is recommended [51].

The environmental impacts of electric motors are less researched. Researchers Nordelof et al. developed a life cycle inventory for electric motors [53, 54, 55]. The end-of-life stage is not included in the research due to limited information available on the procedures. A life cycle assessment using this inventory revealed that the total global warming potential of motors is greatly influenced by the electricity used for production and depends on the share of renewable energy in the electricity grid [56].

Researchers have also examined how the criticality of materials could be included in Life Cycle Assessments (LCAs) [47]. The currently used metric ’abiotic depletion potential’ is criticized for emphasizing material depletion rather than assessing the economic viability of extracting a material [47]. As a solution, Lutkehaus et al. suggested using a new metric called ‘economic product importance’ (EPI) to measure the importance of a particular raw material for a product system [47].

2.5. End-of-life strategies for electric components

Currently, only a small fraction of batteries are recycled while the majority end up in landfills or are stored in households [82]. The recycling process of electric vehicle (EV) batteries is not fully mature yet as many of these batteries are still in use and thus are not available for recycling [67]. It is interesting to note that when batteries in such applications reach their end-of-life stage, they typically retain 70-80% of their capacity [84]. They could be used in secondary applications such as peak-shaving or energy storage in buildings [29, 35, 65, 84].

When other lifetime extensions or circular strategies are no longer feasible, the batteries can still be recycled. Pyrometallurgy, hydrometallurgy, and direct recycling are three main methods of recycling lithium-ion batteries [35, 65, 84, 85]. Pyrometallurgy is a well-developed process to recover valuable metals [82, 84, 85]. However, it has a high energy consumption and high costs [65, 84, 85]. Hydrometallurgy is a more complex recycling method, but it is also deemed cost-effective [84]. More materials can be recovered through hydrometallurgy than pyrometallurgy [82, 84, 85]. Direct recycling offers lower costs [84] and could significantly reduce life cycle emissions [65], but the method is not yet fully mature [85] and cannot be applied to mixed material streams [65].

It is mentioned that research on recycling mainly considers greenhouse gas emissions, sometimes neglecting other environmental impacts [65]. The ideal recycling method would generate the least amount of waste and utilize the least amount of external resources [82]. Additionally, the design of a product should already incorporate solutions to facilitate recycling, such as records of material compositions and disassembly techniques [65].

Limited information and research is available on the possible end-of-life routes for electric motors [80]. Some of the biggest challenges to overcome are that there are different compositions for motors, and additionally the conditions can also vary at the end-of-life based on the operating conditions [46, 80].

NdFeB magnets from electric motors can be recycled through three different routes: pyrometallurgical, hydrometallurgical, or magnet-to-magnet recycling [9]. Pyrometallurgical and hydrometallurgical techniques are often combined [9]. Through such processing, individual materials can be recovered [9]. Magnet-to-magnet recycling is more energy-efficient [78]. The process steps are similar to the conventional manufacturing route [91]. Recycling helps reduce supply uncertainties of REEs such as neodymium, but the complex processes require detailed analysis to determine the economic and environmental benefits. The properties of the magnet could also be affected by the magnet-to-magnet recycling process, leaving them unsuitable for similar applications.

2.6. Magnetic properties

In order to assess the feasibility of recycling magnets or using secondary magnet materials in aviation, more understanding of magnetic properties is required. This section explains the principles behind magnetism in materials. Magnetism arises due to the motion of electrons in atoms, as explained by Callister et al. [14] and Ashby et al. [4]. Electrons orbit the nucleus, and at the same time spin around their own axis. In most materials, the spins of electrons cancel each other out, resulting in no net magnetic moment. However, some materials have residual moments which result in a net magnetic moment that gives rise to ferromagnetism. Due to coupling interactions, magnetic moments align with one another, even in the absence of an external magnetic field. The aligned moments form domains within the grains of a material.

Materials will tend to minimize the external field created by splitting domains into parallel ones with opposing orientations [4, 14]. In a magnetic field, the domains already aligned with the field have lower energy than those aligned against it. The favourably oriented domains grow at the expense of the others, increasing the magnetization of the material. For a solid material, the magnitude of the magnetization field is the vector sum of the magnetizations of all its domains, weighted by their volume fractions.

The magnetic properties of a material are also affected by thermal energy [4, 14]. In most materials, the thermal motion of the atoms is enough to randomize the directions of the magnetic moments. In ferromagnetic materials, the thermal motion is countered by the energy drop resulting from the alignment of magnetic moment, if the temperature is not too high. This is known as the exchange energy [4]. Increasing temperature causes misalignment of the moments and reduces magnetization. Above the Curie temperature magnetisation disappears due to the increased thermal motion of atoms.

Magnetic properties of ferromagnets can be derived from the hysteresis loop shown in Figure 2.4, adapted from Wikimedia Commons[2]. As Callister et al. [14] and Ashby et al. [4] explain, in such a hysteresis loop, the degree of magnetization in terms of the flux density B, or the magnetization M, is plotted against the strength of an externally applied magnetic field H. The relationship between their flux density B and field intensity H is not linear for ferromagnetic materials. When the material is unmagnetized and an H field is applied, B (or M) first builds up slowly. The domain boundaries change: those with the same orientation as H start growing. B then increases more rapidly, until it reaches its maximum value, the saturation flux density Bs (or saturation magnetization Ms). At this point, the material becomes a single domain aligned with the field.

When H field is reduced, the B field does not follow the original path, creating a hysteresis effect [4, 14]. The domain walls resist movement when the magnetic field increases in the opposite direction. When the applied field is reduced to zero, some magnetization remains.

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[2] https://commons.wikimedia.org/wiki/File:Magnetic_hysteresis.png

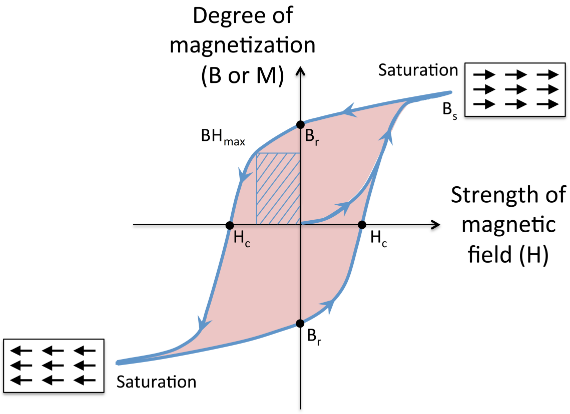

Figure 2.4: Hysteresis loop for ferromagnetic materials, showing the saturation flux density Bs, remanence Br, energy product BHmax and coercive force Hc. Adapted from Wikimedia Commons.

It is called remanence and is denoted by Br in Figure 2.4. In order to completely remove the magnetization, an H field in the opposite direction must be applied. This measure of resistance to demagnetisation is known as the coercivity, or coercive force, Hc. The hysteresis loop also runs to the opposite direction.

In Figure 2.4 one more important parameter is visible: the energy product, BHmax. This value is determined from the largest rectangular area in the second quadrant [4, 14]. The energy product reflects the amount of energy needed to demagnetize a permanent magnet: a higher (BH)max indicates greater magnetic strength and resistance to demagnetization.

2.7. Performance of NdFeB magnets

NdFeB permanent magnets exhibit strong magnetic properties, which derive from their microstructure: grain size, shape and orientation [14]. The microstructure of this material is affected by the manufacturing techniques. Two process routes are common: powder metallurgy (sintering) and rapid solidification (melt spinning) [14]. In the first process, the material is first alloyed and ground into a fine powder. Then, the powder is aligned by applying a magnetic field to it. The aligned powder is pressed into shape and sintered. Another heat treatment is applied to further enhance the magnetic properties of the piece. The rapid solidification method involves quenching the molten alloy quickly in order to create an amorphous or thin solid ribbon, that is then pulverized, shaped, and heat-treated. Although rapid solidification is more complex, it is a continuous process, which has its advantages over a batch process like powder metallurgy. However, most commercially available NdFeB magnets are produced through powder metallurgy and sintering due to the superior magnetic properties [86].

The microstructure of the magnet throughout the sintering production route is depicted in Figure 2.5 [86]. First, a Nd-Fe-B alloy is formed through strip casting: the material is casted onto a rotating wheel that rapidly cools it. This approach results in an alloy with a uniform microstructure consisting of microscale grains [86]. Next, the material is crushed using hydrogen decrepitation (HD) and then further ground using jet milling until the grain size reaches typically 3-5 μm. The resulting powder is then aligned using a magnetic field and pressed into desired shape. The part is subsequently sintered. In the grain boundary diffusion process, REEs such as Dy and Tb, are diffused into the grain boundaries of the magnet. This targeted diffusion process increases the coercivity and results in improved remanence over bulk diffusion processing [86]. The final processing steps include machining, coating and magnetizing.

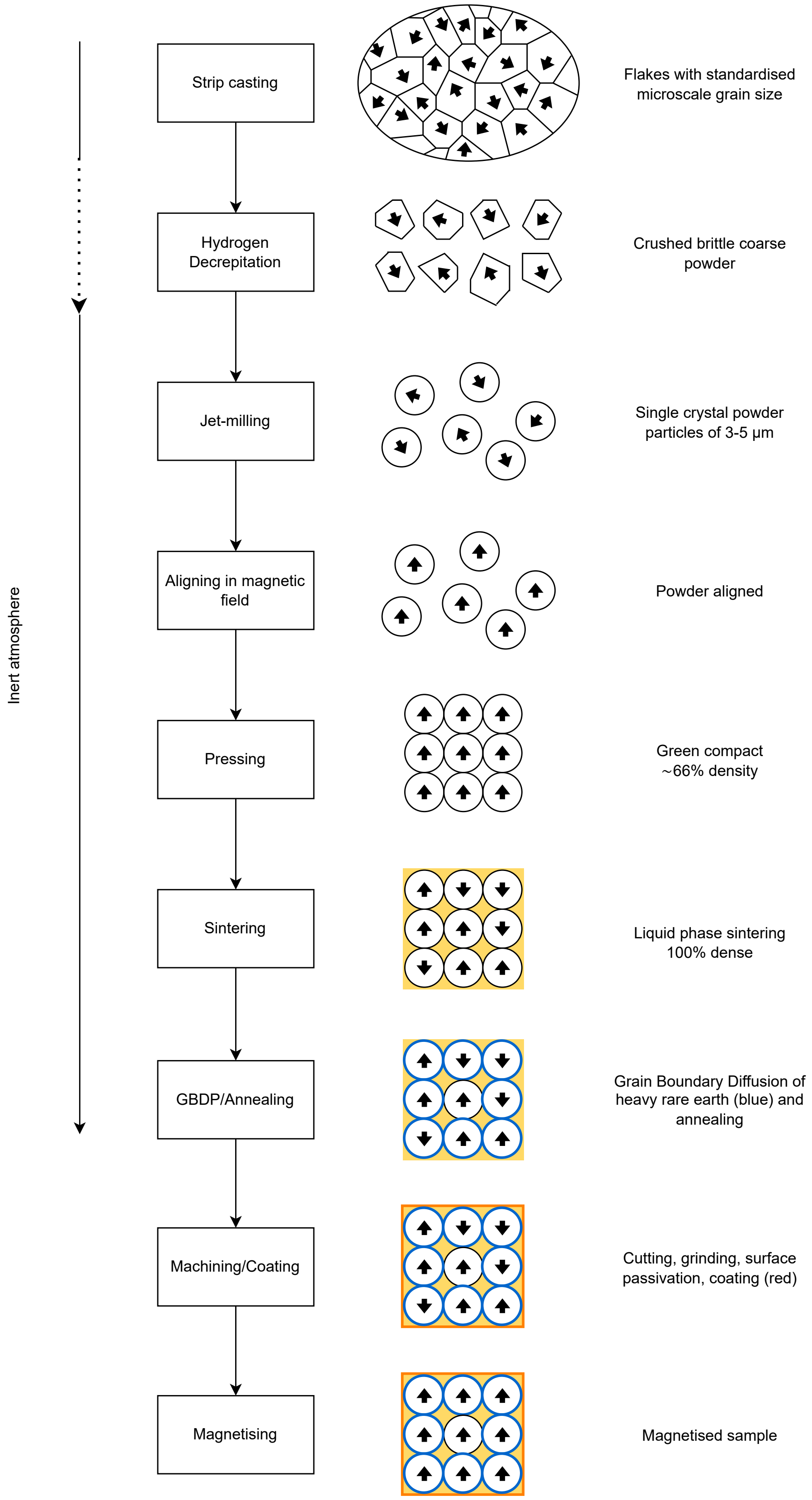

Figure 2.5: Magnet production steps in sintering, and the microstructure of the magnet throughout the production steps. Adapted from Yang et al. [86].

3

Research scope and objective

Based on the literature summarized in the previous Chapter, the objective for this research is formulated. This Chapter presents the scope for the research, the main objective and the research questions. An overview of the methodology is also provided, and some of the research limitations discussed.

3.1. Research scope

This study explores the use of critical raw materials in aviation, as the industry is shifting from conventional aviation fuels to low-emission alternatives. Novel propulsion systems, such as battery-electric and hydrogen fuel cells, require new types of components and therefore also introduce new materials into the aviation sector. Some of the materials needed are considered critical due to their supply risks, like lithium, cobalt, and Rare Earth Elements [10].

These critical materials are essential enablers of renewable energy technologies and electrification [12]. As the demand for such materials increases, the rate of consumption could exceed the rate at which the materials can be supplied [12]. Applying circular economy principles could help reduce demand for primary raw materials in Europe and secure supplies. As critical raw materials and circularity are not commonly researched in the context of aviation, this project aims to investigate circularity strategies for components with critical raw materials in aviation.

The scope of the research is visually presented in Figure 3.1. The key elements are the critical raw materials used in aviation, specifically in future sustainable aviation. Besides combustion of sustainable aviation fuel and of hydrogen, further sustainable energy sources are electric. According to literature, electric aviation can include battery-electric, hybrid, and hydrogen fuel cells aircraft configurations. Batteries and electric motors, particularly Lithium-ion batteries and NdFeB permanent magnet motors, are therefore essential components enabling sustainable aviation in the future. The components contain critical raw materials: battery cathodes include Lithium and Cobalt, and the magnets within electric motors Neodymium and Dysprosium.

3.2. Research objective

The objective of this study is to investigate how circular economy strategies can be utilized for critical raw materials in new electric propulsion systems in aviation. The scope of materials is limited to Lithium and Cobalt in batteries and Neodymium and Dysprosium in electric motors. The research question is formulated as follows.

RQ: What circular economy strategies could be implemented to reduce the demand of critical raw materials in electric aviation by 2050?

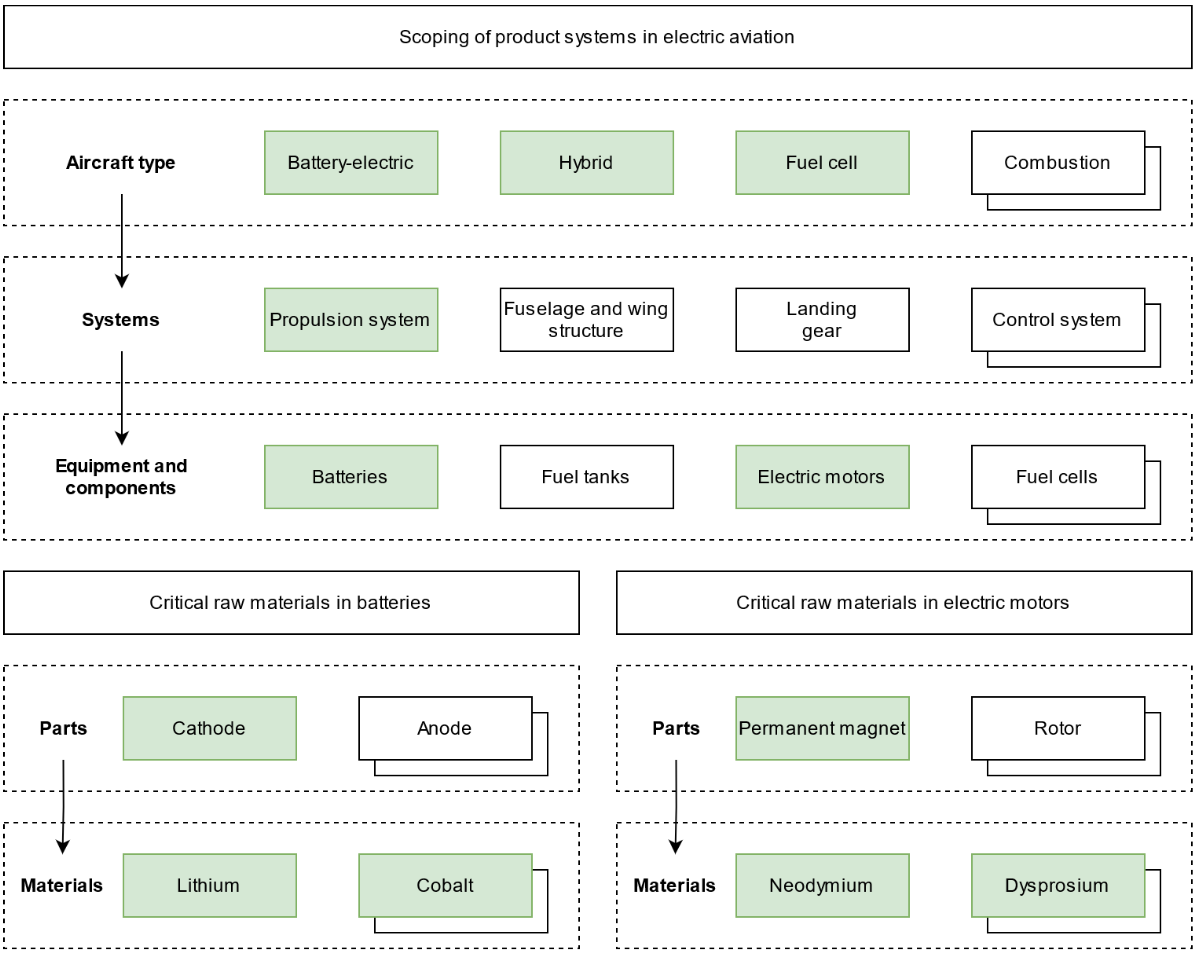

Figure 3.1: The scope for products systems and materials studied in the research. Green colour indicates the route that is in scope for the chosen materials. The highest level of scoping is shown at the top, starting from concepts included in electric aviation, followed by the systems considered, leading to the product systems. The materials interesting for the research are shown per product system.

The study's findings will be used to qualitatively assess what impact circular strategies could have on the critical raw material demand from aviation. Both the material demand and the circular strategies are also evaluated in a wider industrial context.

The research question is further divided into subquestions, as follows.

SQ1: How will the aviation sector develop until 2050?

The first subquestion looks into the technological advancement of the aviation sector. The growth of the aviation sector in general will be considered and technological developments researched.

SQ2: How will the critical raw material demand for aviation develop until 2050?

To answer the second subquestion, possible scenarios in terms of material demand will be modelled. These follow from the answers to the first subquestion and from further data on material concentrations.

SQ3: What requirements apply to the components in aviation?

The performance criteria for the components and for the material properties is studied in the third subquestion. Current designs in development, research on future designs, and component certification considerations will be investigated.

SQ4: Which end-of-life processes are feasible for components and materials in aviation?

The end-of-life condition of components and materials should be investigated first. Furthermore, the impacts of various end-of-life processes on components and materials are evaluated to determine their applicability to the aviation sector.

Finally, the information from all the subquestions will be connected to answer the main research question. Circular economy strategies for aviation components will be evaluated through a general framework, the Resource States Framework developed by Blomsma and Tennant [11]. The components in aviation are used as a case study, and thus the performance requirements from SQ3 are applied to the framework. This results of the research will be presented in a framework adapted for the specific components and materials considered in this research.

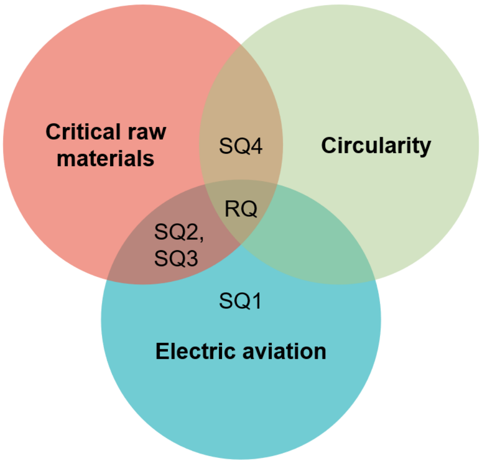

Figure 3.2: Venn diagram showing the intersections of the three research areas. The main research question falls in the intersection of all three areas, whereas the subquestions are divided into the most relevant topics.

Figure 3.2 shows the three overlapping topics of interest in this research: critical raw materials, circularity and aviation. The main research objective and research question combine aspects of all of the topics. Subquestion 1 only considers the development of the aviation sector. The second and third subquestion refer to the specific components and materials used in aviation, and the requirements for them. The fourth subquestion aims to build an overview of possible end-of-life processes for the components and critical raw materials in question. Finally, the results of the subquestions are combined to evaluate circular strategies for critical raw materials with respect to the requirements of electric aviation.

3.3. Overview of methodology and limitations

An overview of the research is visually presented in Figure 3.3. The three main phases are data collection, research steps corresponding to the subquestions, and discussion of the results.

The data collection phase is divided into four main blocks: 1. aviation development, 2. components and materials, 3. component certification and 4. circular strategies. Data on aviation development and propulsion system technology development is further used to build scenarios for the technology deployment until 2050 (B1). When combined with further data on component sizing and material quantities, the material demand can be modelled (B2). The results of the material demand prediction will be evaluated in wider industry context (C1). Here, four materials are looked into: neodymium and dysprosium in the magnets of electric motors, and lithium and cobalt in batteries.

These materials are commonly used in electric vehicles, which is interesting from a research perspective: there is an already existing application, which could either compete with the aviation sector or connect to it through circular material use. Simultaneously, looking at these materials specifically does create a limitation to the research, as some technologies that could be interesting in the future are excluded, such as Li-S batteries.

For further research looking at circular strategies, the scope is narrowed down and the focus is set on electric motor magnets. When component performance in aviation is assessed with certification requirements, a list of design criteria for the electric motors and the corresponding magnet material properties can be established (B3). Circular end-of-life routes are studied for the motors and the magnets. The feasibility of end-of-life practices is assessed based on theoretical data on circular strategies and the already established performance requirements (B4). The Resource States framework can be applied in the context of electric aviation, for the case study of electric motors (B4). Finally, combining the results of the research, the impacts of circular strategies on the material demand are evaluated qualitatively (C2).

One of the main limitations of the research is data availability. The methodology set-up is theoretical, thus no experiments are conducted. Therefore, the research relies heavily on secondary data. Additional challenge is that the electric aviation sector is still developing, which also means that there is limited existing data and theoretical estimations available.

Additionally, the research only considers the technical performance requirements for materials and components and the framework for circular strategies will be based on those. The societal, economic, and environmental impacts of end-of-life strategies are not investigated. Other considerations such as the mentioned mentioned above could eventually be incorporated into the theoretical framework.

Further limitations of the research and the results will be included in the discussions of the results and in the conclusions.

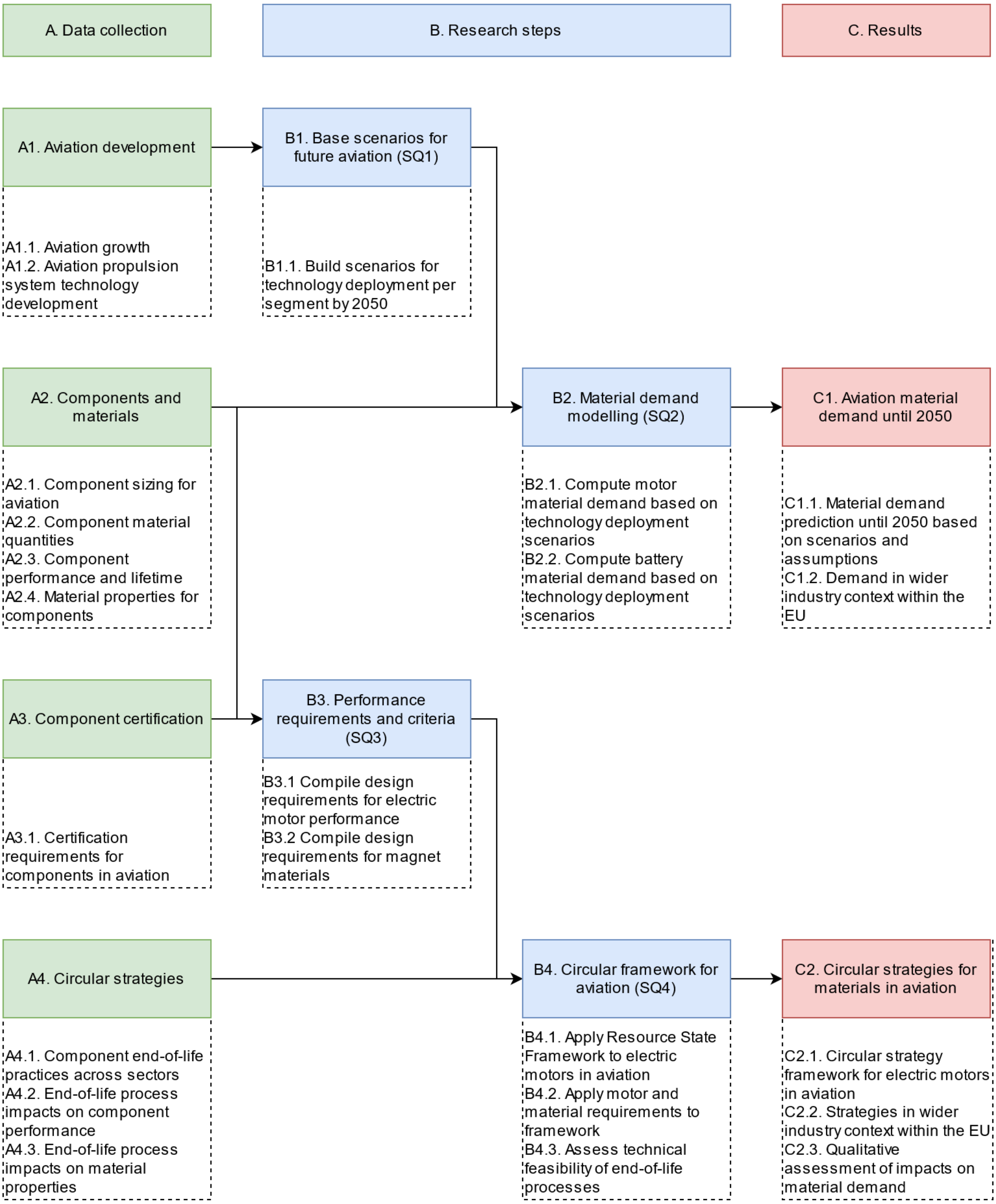

Figure 3.3: Research design showing the three main phases: data collection, research steps and results. Each one is divided into further blocks that describe the relevant data output that should be obtained or the processing steps that need to be taken.

4

Material demand prediction

The first part of the research considers modelling the material demand of critical raw materials in aviation. First, the data collected for the model is discussed. Then, the methodology, thus the model set up, is presented. The results are shown and finally, a discussion of the results is provided.

4.1. Data collection

Material demand predictions for aviation are built with data gathered from literature and industrial examples. The prediction is made considering parameters such as aviation growth, technology development in aviation and component sizing. All of this information is combined together in Section 4.2 in order to build a prediction model. First, data is gathered on the segments in commercial aviation and their sizes. After this, the growth and the development of the aviation industry towards the future is studied. Finally, data on the components and their constituents is looked into.

4.1.1. Aircraft segments

To assess the material demand in the aviation industry and how its develops towards the future, the size of the commercial fleet needs to be studied first. The commercial fleet must transition towards more sustainable alternative fuels. Some of these can be implemented with existing propulsion systems, such as combustion of sustainable aviation fuel, whereas some require new technologies, like batteries and fuel cells. However, the different propulsion technologies available in the future are not applicable to every aviation segment.

The size of the current commercial fleet is estimated to be about 27,000 aircraft, including the commuter section [5, 63]. The report by McKinsey & Company [50] shows the different segments in the aviation sector, their share of the global fleet and their shares of the total CO2 emissions. These values are shown in Table 4.1. Similarly, the Oliver Wyman market forecast report gives aircraft fleet numbers for certain segments, which can be converted to shares of the global fleet [63]. This report uses the Cirium database[1], which is also the basis for the Waypoint report by The Air Transport Action Group (ATAG). The commuter section is said to cover 1750 aircraft [5], which corresponds to about 6.5% of the global fleet. From the numbers in the Oliver Wyman report, the regional section is calculated to add up to about 19% of the total global fleet and the narrowbody (short-range) to about 56% [63], also shown in Table 4.1.

It should be noted that the main CO2 emissions during operations come from the larger aircraft with long-haul flights [50]. Due to the high energy needs, it is also difficult to convert these segments to more sustainable fuels. In terms of material demand, the short-range segment is interesting as it has the highest number of aircraft out the total commercial fleet.

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[1] https://www.cirium.com/data-innovation/aviation-data-sets/

[1] https://www.eea.europa.eu/ims/new-registrations-of-electric-vehicles

Table 4.1: Aircraft segments and their shares from McKinsey & Company [50] and Cirium database [5, 63].

Segment	Seats	Share of CO2 emissions [50]	Share of global fleet [50]	Share of global fleet [5, 63]
Commuter	<19	<1%	4%	6.5%
Regional	20-80	3%	13%	19%
Short-range (narrowbody)	81-165	24%	53%	56%
Medium-range	166-250	43%	18%	-
Long-range	>250	30%	12%	-

4.1.2. Aviation growth

Aviation growth is often noted in Revenue Passenger-Kilometers (RPKs), which describe the actual demand in air traffic. RPKs are calculated as the number of paying passengers multiplied by the kilometres flown. Predicted aviation growth slowed down due to Covid-19 pandemic, but it is expected to increase again in the coming decades [5, 37].

For 2018-2050 forecasts from ICAO prediction show three scenarios. Compound annual growth rate (CAGR) of RPKs is 2.9% in the low, 3.6% in the medium, and 4.2% in the high scenario. ATAG also predicts RPK CAGR for the period 2019-2050 [5]. Again, three scenarios are presented: 2.3%, 3.1% and 3.3%. In their report, Clean Sky 2 [17] does not present forecasts for RPK, but instead predicts passenger volume growth scenarios. Excluding the limitations from airport capacities, the low scenario shows 3.5% CAGR for 2014-2050, and the high one 4.1%. These values are close to the high RPK values of ICAO [37] and ATAG [5]. In the Clean Sky 2 report [17] it is argued that aircraft will fly shorter distances - combined with the increasing passenger numbers presented this supports the RPK values shown in the other two reports.

4.1.3. Technology development

In this assessment possible technologies are only divided into combustion, battery-electric, hybrid, and fuel cell. Combustion aircraft in this case can burn other fuels besides kerosene, for example sustainable aviation fuel (SAF) and hydrogen. The fuel used for combustion is not specified further, as it is assumed that the combustion aircraft in general will not contain the propulsion system components evaluated here: electric motors and batteries.

Moving towards sustainable aviation, the contribution of SAF is extremely important. It is a drop-in fuel; it can be directly used in current AC designs and engines. Similarly, the existing fuel distribution infrastructure can be used. However, it cannot be produced in large enough quantities to cover all of aviation. Estimates for CO2 emission reductions achieved in aviation by switching to SAF range from 5% to 70% [5, 17, 36], depending on SAF availability. SAF is applicable to large aircraft, unlike battery-electric and hydrogen fuel cells. Therefore, in this study, it is assumed that SAF contributes mainly to larger AC where other options are limited.

The feasibility of propulsion systems (battery-electric, hybrid, hydrogen fuel cells) across aviation sectors in uncertain. The impact on aviation CO2 emission reductions is highly dependent on technology development. IATA estimates 13% reductions through new technologies (incl. hydrogen combustion), which indicates that SAF is seen as a much more likely option for decarbonization over new propulsion systems [2].

The McKinsey & Company report [50] identifies commuter, regional and some short-range as possible for battery-electric aircraft. It is mentioned that new designs are needed to enable

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[2] https://www.iata.org/flynetzero/

hydrogen combustion for medium-range and long-range. Hydrogen fuel cells could be implemented in the commuter, regional and partly also in the short-range segments. The report assumes two scenarios for hydrogen development: an efficient scenario where all aircraft in the commuter to short-range and 50% of medium-range could be powered by hydrogen (fuel cells and combustion), and a maximum decarbonization scenario, where most medium-range and some long-range aircraft also use hydrogen (combustion).

ATAG [5] describes different technology development paths for the sector. Battery-electric propulsion is assumed to become available for the commuter and regional segments. In the most advanced technology development path electric aircraft would become available in the 51-100 seat segment from 2038 onwards. Similarly to the McKinsey & Company report [50], ATAG [5] also argues that new designs are required for larger hydrogen aircraft. The advanced technology development scenario includes hydrogen aircraft in the 101-200 seat segment from 2035 onwards.

Clean Sky 2 [17] estimates that regional, short-range and medium-range segments will decline in the future, whereas the demand for large aircraft will increase. Large aircraft would be the most economical option due to airport growth constraints. Rather than increasing the number of operational aircraft, airlines could maximize passenger capacity on a route [17]. The share of large AC above 300 seats would be between 15% and 30% (excluding aircraft of <19 seats), depending on the constraints by the airports.

For this research, only the smaller segments are considered due to the applicability of new technology. The shares of large and medium-sized aircraft over the years are not considered further. It is likely that the share of the short-range segment with narrowbody aircraft would be affected by the growing share of larger aircraft, but this consideration is not included in this evaluation. The shares of the commuter, regional and short-range segments are assumed constant over the years. The prediction does not include the possible introduction of urban air mobility vehicles. These could be counted towards the commuter segment, if they were to be included in a future assessment.

4.1.4. Components for electric aviation

Since electric aviation is not yet commercially available, there is not much existing data on components used in such aircraft. However, there are theoretical designs for hybrid and battery-electric aircraft [22, 29, 67, 70] and there are companies developing electric aircraft. The available designs are presented in Table 4.2. These are used as a reference for determining how components are sized across the segments.

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[3] https://www.pipistrel-aircraft.com/products/general-aviation/velis-electro/

[4] https://www.nasa.gov/specials/X57/

[5] https://www.dlr.de/content/en/images/dosiers/electric-flight/hy4-airport-dossier-e-flight.html

[6] https://aerotec.com/magnix-and-aerotec-announce-successful-first-flight-of-the-worlds-largest-all-electric-aircraft/

[7] https://www.eviation.com/aircraft/

[8] https://www.zeroavia.com/

[9] https://www.ampaire.com/

[10] https://www.zeroavia.com/

[11] https://maeve.aero/echelon

[12] https://sacd.larc.nasa.gov/asab/asab-projects-2/pegasus/

Table 4.2: Electric aircraft designs available and in development. The technology types are abbreviated as battery-electric (BE), hybrid (H) and fuel cell (FC). The segments are general aviation (G), which is not for commercial routes, commuter aircraft (C), and regional aircraft (R). Motor power is given as the total motor power available from all motors, listed as continuous power (if differentiation has been available). Similarly, battery size is the total available energy from batteries. Auxiliary energy sources are marked with (aux.).

Aircraft	**Developer**	**Type**	**PAX seats**	**Segment**	**Motor power [kW]**	**Battery size [kWh]**	**Source**
Velis Electro	Pipistrel	BE	1	G	50	25	Pipistrel[3]
X-57	NASA	BE	1	G	246	70	NASA[4] [33]
HY4	DLR	FC	3	G	80	21 (aux.)	[66] and DLR[5]
eCaravan	AeroTEC	BE	5	C	560	-	AeroTEC[6]
Alice	Eviation	BE	9	C	1280	920	[66] and Eviation[7]
ZA-600	ZeroAvia	FC	9	C	600	-	ZeroAvia[8]
Eco Otter	Ampaire	H	19	C	1000	-	Ampaire[9]
ZA-2000	ZeroAvia	FC	40	R	2000	-	ZeroAvia[10]
Maeve 01	Maeve	BE	44	R	8696	-	Maeve[11]
PEGASUS	NASA	H	48	R	5443	-	NASA[12] [15]

4.1.5. Magnet materials

From the reference aircraft shown in Table 4.2, it is known that the NASA designs, the eCaravan, and the Velis Electro use permanent magnet motors. Permanent magnet synchronous motors offer high efficiency, and in this study, it is assumed that all electric aircraft would use Neodymium-Iron-Boron (NdFeB) permanent magnet motors.

Nordelöf et al. [53, 54] have developed a Life Cycle Inventory for electric motors. According to the LCI model [53], the permanent magnets in NdFeB motors consist of 22-32% neodymium (Nd) and up to 10% dysprosium (Dy). Six motor case studies of different sizes are provided with their respective magnet masses, shown in Table 4.3. Nd and Dy quantities for the motors can be derived from assuming a certain percentage of material within the given range.

For further use, it is interesting to relate the Nd and Dy quantities to the kW output of the motor, because the size of electric motors for aircraft is often presented in kW provided. Thus, the Nd and Dy quantities should be formulated as a function of the kW output. A linear statistical relationship can be built between the kW value and the material quantity based on the six cases and their magnet masses as shown in Table 4.3. Here, the motors use approximately 0.014 kg of magnets per kW output [53]. This is comparable to another study on the automotive sector, where the magnet size needed is assumed 0.012 kg per kW [57]. Additionally, the magnet composition is assumed based on the given range (Nd mass 22-32% of magnet, Dy mass up to 10% of magnet). In this way, materials needed can be predicted based on estimated or listed motor sizes for specific aircraft segments.

Here it is assumed that when the composition percentage is fixed, the same amount of magnetic material would be needed for every motor of a certain kW output, regardless of other differences or properties of the motors.

4.1.6. Battery materials

The batteries are assessed based on the data from Wang et al. [83], Rajaeifar et al. [65], and Li et al. [43]. In the analysis of Wang et al. [83], three cathode chemistries for lithium-ion batteries (LIB) are presented. The LiCoO2 – lithium cobalt oxide – based LIBs contain on average 17.5% cobalt out of the total cathode weight, whereas LiFePO4 and LiMn2O4 do not contain any cobalt. The cathode itself is about 25% of the battery weight [65], which means

Table 4.3: Six motors of different sizes presented in LCI model with respective magnet masses [53]. Neodymium mass is calculated assuming it is 27% of magnet weight and dysprosium mass assuming 5.5% of magnet weight.

Motor power [kW]	Magnet mass [kg]	Nd mass [kg]	Dy mass [kg]
20	0.32	0.086	0.018
40	0.65	0.176	0.036
50	0.62	0.167	0.034
80	1.29	0.348	0.071
100	1.25	0.338	0.069
200	2.49	0.672	0.137

that about 4.4% of the total battery weight is cobalt. All batteries in the assessment of Wang et al. contain between 1.2% and 2.0% lithium [83].

According to Rajaeifar et al. [65], batteries include about 1.8% lithium of the total mass, which is in line with the values from Wang et al. [83]. The presented chemistries with cobalt, lithium nickel manganese cobalt oxides (NMC), contain about 3% cobalt out of the total battery weight, which also supports the results of Wang et al. [83].

Researchers Li et al. write that state-of-the-art NMC batteries use between 80-200 g of cobalt per kWh [43]. If one assumes that these batteries can reach an energy density of 250 Wh/kg, it would mean that between 2-5% of the battery weight is cobalt. This value is again close to those provided by both Wang et al. [83] and Rajaeifar et al. [65].

Currently, there is a trend towards lower cobalt use in batteries [6, 65, 94]. The Li-S chemistry that is proposed for aviation applications in the future does not contain cobalt. However, Li-ion batteries with NMC cathodes are the most common batteries used now [29, 43, 65]. Although Li-S might take over in the future, it is assumed that Li-ion will stay relevant for aviation applications even in the long-term, as it is already commercially available. Additionally, certification of new battery chemistries for aviation purposes could slow down the introduction of chemistries beyond Li-ion.

4.2. Methodology

To build up the model, first an assumption on how the aviation industry looks like in 2050 needs to be established, showing to what extent the electric propulsion system technologies are implemented by then. Only then the material quantities needed to arrive to this future scenario can be computed. Here, the logic and the flow behind the demand prediction simulation are explained.

4.2.1. Scenarios for 2050

As discussed in Chapter 2, the demand for critical raw materials is increasing considerably by 2030 and beyond [12]. Electric aviation is expected to take off after 2030, and the aviation industry is targeting to reach net-zero by 2050. The goal here is to build three technology deployment scenarios for the future: a low, a medium and a high scenario. The reasoning behind opting for three scenarios is to cover some uncertainties in terms of technology development paths and market interests. In addition to the considerations from Section 4.1, further topics are addressed to qualitatively predict the technology developments across the segments.

Technological developments

First of all, the technology deployment scenarios are based on the assumption that technology development will take place – a scenario where the aviation industry continues to grow but only using current technologies is not relevant for this research, nor supported by literature.

The main limiting factor from the technology side is the requirement for lightweight energy carriers. Fuel cell aircraft are challenged by the volume required for energy storage. As hydrogen tanks and fuel cells themselves are not considered in this report, it will not be discussed in more detail. For hybrid and battery-electric aircraft the situation is more dire: as discussed in Chapter 2, current battery technology cannot compete with kerosene as an energy carrier. Lithium-ion batteries have the highest specific energy densities from different battery technologies, reaching 250 Wh/kg [66, 69]. To compare this value, kerosene has an energy density of about 12,000 Wh/kg [66, 69]. It is expected that Li-ion batteries could reach 350 Wh/kg [66]. Other future battery technologies, such as lithium-sulfur (Li-S) and lithium-air (Li-air) are estimated to reach higher specific energies. Their development would support further application of battery-electric and hybrid aircraft across commuter and even regional segments beyond 2030.

On the other hand, lifetime of aircraft is about 30 years, which means that almost all aircraft flying today will have to be replaced by the year 2050. This is an opportunity to replace the fleet with more sustainable propulsion systems. However, electric technologies are not yet readily available, which means that at least until their commercial introduction, kerosene and SAF combustion will be the leading means of propulsion. Additionally, electric technologies are only applicable to smaller aircraft due to low battery energy densities: hybrid and electric propulsion systems are focused on the commuter and regional segments. The main developers for these types of aircraft are start-ups and small companies. Fuel cell development is aiming at the regional and short range segments and the leading developer is the manufacturing giant Airbus[13]. For the aforementioned reasons, only commuter, regional and short-range (narrowbody) segments are included in the future scenarios.

Regulations

Another barrier for electric aviation is rooted in the regulations. The European Aviation Safety Agency (EASA) has identified that the certification specifications applied to aircraft do not cover electric or hybrid propulsion systems [20]. Therefore, EASA has published a Special Condition that determines objective-based requirements for such propulsion systems [20]. This Special Condition is meant to support certification of electric and hybrid aircraft regardless of the propulsion system architecture. However, in the case of large-scale adoption of electric aviation in commercial aviation, it is possible that new regulations need to be made for the specific propulsion system architectures. Commuter aircraft segment falls under the CS-23 specification. Larger aircraft are certified under the CS-25. In this research all technology deployment scenarios assume that a new propulsion system needs to be tested on CS-23 aircraft before it can be applied to CS-25 aircraft.

Policies

There is a drive towards more electric aircraft from policymakers and from the industry. The sector is pushing for lower emissions in aviation, as discussed in Section 4.1.3. Some European governments have published statements on their emission reduction goals. Sweden has stated that all domestic flights should be CO2-free in 2030 and international flights by 2045[14]. Norway is planning on electrifying domestic flights by 2040[15]. Industry developments for elec-

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[13] https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe

[14] https://fossilfrittsverige.se/en/roadmap/the-aviation-industry/

[15] https://avinor.no/en/corporate/klima/electric-aviation/electric-aviation

Table 4.4: The three technology deployment scenarios for 2050. Technologies shown here are battery-electric (BE), hybrid (H), and fuel cell (FC). The assumed segment shares of global fleet are shown in percentages after the respective segments. The percentages show the share of each technology within a segment. Total shares of propulsion system technologies are presented on the bottom row.

Scenario:		**Low**			**Medium**			**High**		
Technology:		BE	H	FC	BE	H	FC	BE	H	FC
Commuter	6%	20%	40%	10%	40%	30%	10%	60%	20%	10%
Regional	15%	0%	20%	20%	0%	20%	30%	10%	20%	40%
Short-range	55%	0%	0%	0%	0%	0%	10%	0%	10%	20%
Technology share of global fleet		1.2%	5.4%	3.6%	2.4%	4.8%	10.6%	5.1%	9.7%	17.6%

tric aviation are shown in Table 4.2. The battery-electric and hybrid designs are expected to be commercially available before 2030, and the fuel cell aircraft soon after. This estimate is based on the reference aircraft, see Table 4.2, and on announcements on the development of hydrogen-powered aircraft[16].

Here, only European aviation is discussed, but the growth of the sector is applicable worldwide. In order to reduce the emissions from aviation globally, technology development and transitioning to alternative fuels should take place globally as well. The pace at which technology changes can be achieved will likely be high in Europe, where industry and policymakers are pushing for sustainable aviation. However, it is assumed that globally kerosene combustion will still play a significant role in the aviation sector.

The qualitative assessment above and the data from Section 4.1.3 is translated into the assumed values presented in Table 4.4. The scenarios show the assumed shares of certain technologies across segments in the year 2050. The upper limits are identified: even if all commuter aircraft could in theory be electrified, it is unlikely that this would take place by 2050, because battery electric aircraft are not fully commercial yet and some kerosene-powered aircraft will still have years left in their useful lifetime by then. Fuel cell aircraft could potentially be deployed in the short-range segment, which is reflected in the high technology deployment scenario. The low deployment scenario assumes that countries follow up on their targets to electrify aviation, and that commercialization of techonologies is achieved. Going from low to high deployment scenario, a shift from hybrid to more battery-electric aircraft is assumed.

The three technology deployment scenarios will be used to compute the material demand prediction and to evaluate the impact of technology development paths on the material demand. It is interesting to point out that not all technologies are increasing their shares from the low deployment to the high deployment scenario. Hybrid aircraft for example are seen to have lower shares in the commuter sector as battery-electric aircraft become more widely adopted. The largest difference in shares comes from the fuel cell technology, which in the low deployment scenario is only adopted in the commuter and regional segments. In the high deployment scenario, fuel cell aircraft become widely adopted also in the short-range segment, increasing the share of the technology across the global fleet significantly.

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[16] https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe

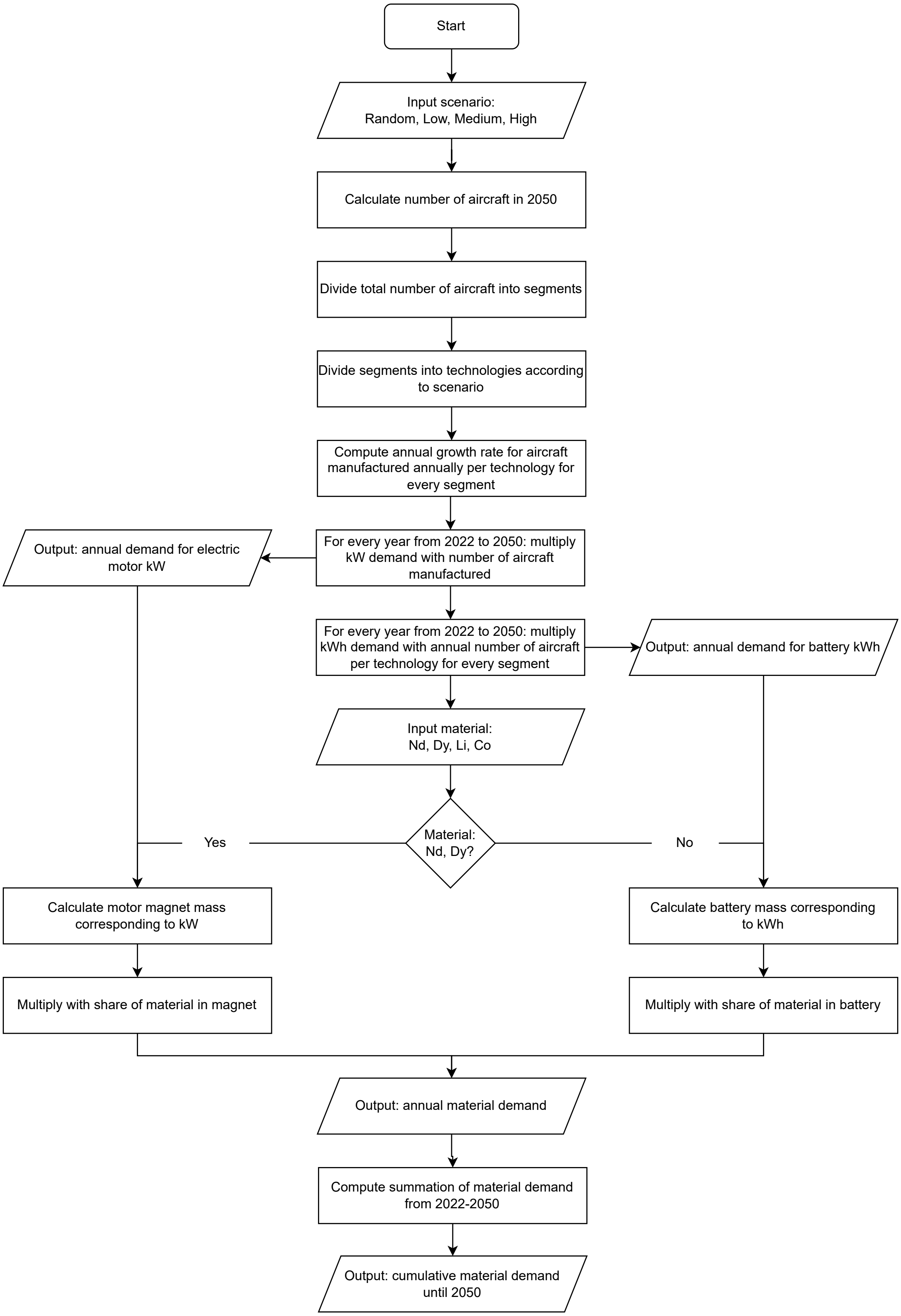

Figure 4.1: Code flowchart for the material prediction modelling.

4.2.2. Flow

The calculation method for modelling cumulative material demand for electric aviation is visually presented in a flow chart in Figure 4.1. This flow logic is used to write a simulation program that can run the model with given input parameters. The assumed fixed input parameteres are listed in Table 4.5 and the assumed variables in Table 4.6.

In order to examine the uncertainty of the assumptions, most of the variables are given a range in a uniform distribution, see Table 4.6. The simulation can then be run with inputs chosen randomly from within this range. When the simulation is run multiple times, most of the possible variable combinations can be covered. Then, fixed variable scenarios are built based on the mean values and the three technology deployment scenarios. These are assessed with respect to the full range of simulated solutions to make final predictions of material demand.

Aviation development

To run the model, first, the input scenario for technology development is chosen from the scenarios described in Subsection 4.2.1 and shown in Table 4.4. For randomized variables, the low and high scenario are taken as the boundaries. For the random scenario, variables can be determined from an uniform distribution between this minimum and maximum. The scenario is then used to compute the setting for 2050.

The number of aircraft flying in 2050 is based on the number of aircraft in 2022 and the compound annual growth rate. With the assumed size of current fleet and CAGR of 3.2% as presented in Table 4.5, in year 2041 the number of aircraft would be 49,000. For validation of this number it is compared to the estimation of Airbus [75] from 2022, which expects 46,930 aircraft in 2041, excluding commuter aircraft of 9-19 seats. The assumptions build up to the same magnitude.

The segment shares within the global fleet are assumed to stay constant from 2022 to 2050. The technology shares within each segment in 2050 are derived from the technology deployment scenarios in Table 4.4. Now, the number of aircraft of a certain technology (battery-electric, hybrid, fuel cell) within each segment (commuter, regional, narrowbody) in 2050 is known. With the assumed year of commercial introduction, and the assumed number of aircraft at the beginning of commercialization, the rate at which each technology progresses within every segment can be computed. The number of new electric aircraft introduced every year is assumed to be increasing and the technology development is assumed to take place at a constant annual rate. With the computed annual rate of development, the number of aircraft of a certain technology, within every segment, can be computed for every year between 2022 and 2050.

The starting year of commercialization for each technology per each segment is assumed based on the data gathered from the companies developing new electric aircraft. These values are taken from the estimated years when companies expect their products to become commercially available, see Table 4.2. Additionally, the number of aircraft introduced depends on the segment and the technology. As large companies like Airbus[17] are developing fuel cell aircraft for the regional and short-range segments, these are assumed to be introduced in greater numbers than for example battery-electric aircraft in the commuter and regional segments, where start-ups are active in the development of aircraft.

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[17] https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe

[18] https://www.eviation.com/aircraft/

[19] https://maeve.aero/echelon

[20] https://www.weflywright.com/technology

Table 4.5: Fixed parameters for the material prediction modelling. Data sources used and assumptions made are explained in Section 4.1. Reference aircraft are chosen for the three segments. It is assumed that all of the power is supplied by electric motors, and that regardless of the hybrid configuration the degree of energy hybridization stays constant.

Fixed parameters

Parameter		**Value**	
Number of aircraft (2022)		27,000	
Share of global fleet			
Commuter		6%	
Regional		15%	
Narrowbody		55%	
Required motor output [kW]			
Commuter		1280[18]	
Regional		8700[19]	
Narrowbody		20,000[20]	
Degree of energy hybridization		0.5	
Battery energy density (2022) [Wh/kg]		250	
Starting year and number of AC introduced			
Commuter	Battery-electric	2030	10
	Hybrid	2025	10
	Fuel cell	2030	10
Regional	Battery-electric	2035	20
	Hybrid	2030	20
	Fuel cell	2035	40
Narrowbody	Battery-electric	NA	NA
	Hybrid	2040	20
	Fuel cell	2040	40

Motor materials

In order to compute the material demand in the components, electric motors and batteries, for every year from 2022 to 2050, the number of battery-electric, hybrid and fuel cell aircraft in every segment is first multiplied with the assumed sizes of the electric motors needed. These are based on reference aircraft: Alice Eviation for the commuter[21], Maeve for the regional[22] and Wright fuel cell system for short-range [23]. It is assumed that all power for the aircraft should be able to be supplied by electric motors, regardless of configuration, even in the case of parallel and series hybrid aircraft. This means that the degree of power hybridization is always 1. From here, the total motor power required per year is computed, which allows to calculate the material demand.

The relationship between the Nd and Dy material demand and the kW size of the motor is built based on the LCI by Nordelöf et al. [53], as described in Subsection 4.1.5. The linear relationship between magnet material and motor output in kW is then used to calculate the annual demand of material according to the input scenario. At first, no component replacements are considered. These are included in the second simulation and will be discussed at a later stage.

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[21] https://www.eviation.com/aircraft/

[22] https://maeve.aero/echelon

[23] https://www.weflywright.com/technology

Table 4.6: Variables for the material prediction modelling. For each variable, a mean value is given, a distribution assumed and a deviation given. Data sources used and assumptions made are explained in Section 4.1.

Variables

Variable	Probability function	Value
CAGR	Mean	1.032 (3.2%)
	Distribution	Normal
	Standard deviation	0.0045
Magnet material composition, Nd	Mean	27%
	Distribution	Uniform
	Boundaries	22%, 32%
Magnet material composition, Dy	Mean	5.5%
	Distribution	Uniform
	Boundaries	1%, 10%
Battery material composition, Li	Mean	2%
	Distribution	Uniform
	Boundaries	1.8%, 2,2%
Battery material composition, Co	Mean	2.5%
	Distribution	Uniform
	Boundaries	0%, 5%
Battery energy density (2050) [Wh/kg]	Mean	2350
	Distribution	Uniform
	Boundaries	2000, 2700
Battery-electric AC required battery energy capacity	Mean	2.5h
	Distribution	Uniform
	Boundaries	1.5h, 3.5h

Battery materials

Similarly, as with the total power demand per year, the total battery energy capacity required by all aircraft can be computed for every year. Here the number of battery-electric, hybrid and fuel cell aircraft in every segment is multiplied with the assumed size of battery needed for each aircraft. It is assumed that fuel cell aircraft will not require a battery.

For battery-electric aircraft it is assumed that in the future, between now and 2050, the batteries should cover 1.5-3.5 times the output kW of the motor. In this case, the aircraft would be able to fly between 1-3h on full continuous power, and additionally have 30 minutes of reserve for holding or diversion. Here it is suggested that these flight times would allow for commercial use of electric aircraft. In order to enable battery-powered flights, design changes are needed not only in airframes and propulsion systems but also in the operational profiles – with low energy densities, electric aircraft become heavy and are not able to operate the same routes or for as long as combustion aircraft. Realistically aircraft will not fly in cruise on full power, thus full power would be reserved for take-off only. A reserve of 30 minutes is assumed, as the regulations for required reserves for electric aircraft are not standardized yet.

For hybrid aircraft, the degree of energy hybridization is assumed as 50%. Thus, regardless of hybrid configuration, the batteries should be able to provide half of the energy for operations.

Additionally, the energy density of batteries is estimated to develop into the future. The minimum value that should be reached by 2050 is taken as 2000 Wh/kg. Lithium-ion batteries cannot reach such energy densities, thus it is assumed that other lithium-based battery technologies could become commercially available before 2050, such as lithium-Sulphur and lithium-air. The theoretical limit for Li-S is estimated at 2700 Wh/kg, which is why this value is chosen as the upper limit. The energy density value for each year is then determined based on a linear development rate from current value to the value in 2050. The chemistries of future batteries are not yet known, thus for this prediction the lithium content is assumed to stay similar to that of Li-ion batteries. Cobalt however might disappear completely from batteries, so the minimum is set as 0%.

The annual material demand is computed with one set of random or fixed values according to the scenario (low, medium, high or random) for every year between 2022 and 2050. Then these are compiled into a cumulative material demand. The simulation is run 1000 times with a different set of values each time. The cumulative demand can be used to evaluate the development of material demand until 2050, and to compare it to other industries and to the predictions for the material demand in general.

4.3. Results of material prediction

In this Section, the results model are presented. First, the materials neodymium and dysprosium used for electric motors are considered, and then the battery materials lithium and cobalt. A second assessment is also made, including possible component replacements.

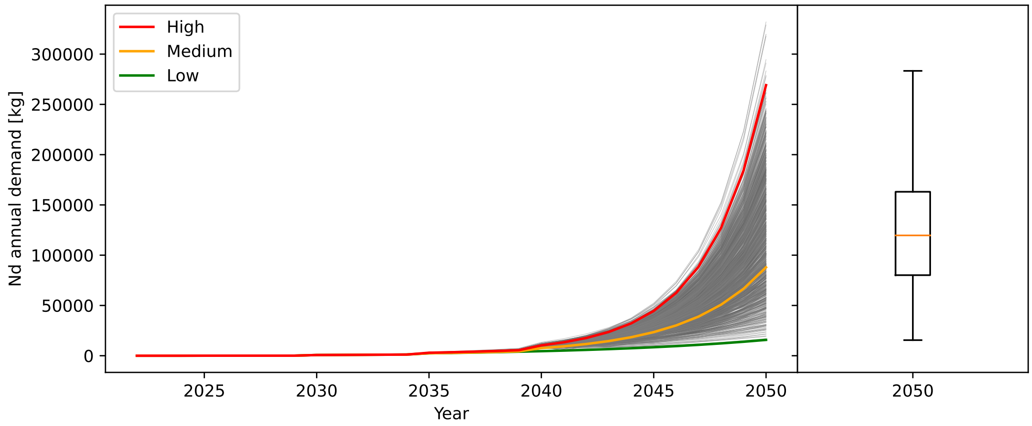
4.3.1. Electric motors

The calculation results in one commuter aircraft requiring 4 kg of Nd and 0.8 kg of Dy, one regional aircraft requiring 28 kg and 5 kg respectively, and lastly, a short-range narrowbody aircraft requiring 64 kg and 12 kg of the REEs, respectively.

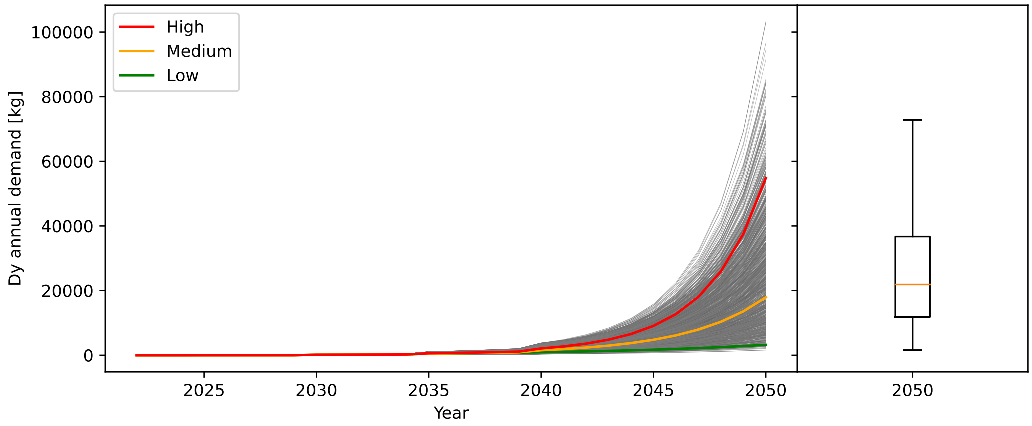
The annual material demand for electric motors in aviation from 2025 to 2050 is presented in Figure 4.2. The figure shows two materials used in the magnets of the motors: neodymium and dysprosium. The graphs are based on running the demand forecast simulation 1000 times with the fixed parameters from Table 4.5 and the variables varying between the boundaries shown in Table 4.6. Component replacements are not yet included in the simulation. At first, in the years of new technology introductions (2025, 2030, 2035, 2040), the graph shows stepwise increments due to the sudden addition of a number of new aircraft into the market. Due to the assumed introduction of most technologies after 2030 or even 2035, the demand rises slowly towards 2040. Beyond 2040, the material demand grows explosively. This follows from the assumption of a constant annual technology growth rate, leading up to the scenarios built for 2050.

Here it can be seen that the uncertainty range for material demand is wide: for Nd, the material demand in the year 2050 could range between 20 tonnes and 270 tonnes, depending on the scenario and the chosen parameters, as seen in Figure 4.2a. For Dy, this range in 2050 is between 2 tonnes and 60 tonnes, shown in Figure 4.2b.

The box plots on the right side show the distribution of the demand curves and indicate the median of the results. For Nd, according to the scenarios and assumptions made, the demand is likely to be between the lower and upper quartiles of the box plot, thus between 80 and 160 tonnes in 2050. The median is at 120 tonnes. Cumulative demand for Dy in 2050 can be estimated to be between 11 tonnes and 36 tonnes. The median stands at 22 tonnes. With both Nd and Dy, the median comes close to the set medium scenario, where the parameters are fixed to their mean values. As can be seen from the curves beyond the highlighted scenarios, the other parameters still add variations, especially in the case of Dy.



(a) Graph for annual demand of neodymium from 2022 to 2050, and a box plot of the demand in 2050

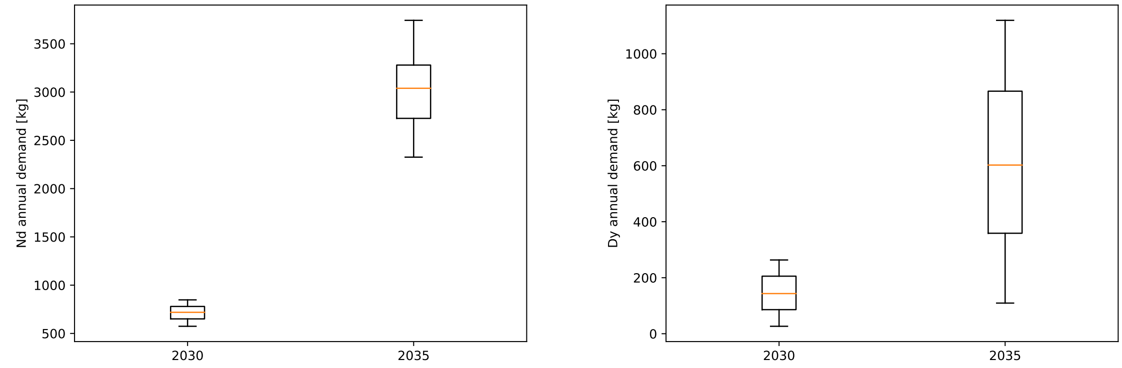


(b) Graph for annual demand of dysprosium from 2022 to 2050, and a box plot of the demand in 2050

Figure 4.2: Forecast of annual material demand for electric motors in aviation from 2022 to 2050

Additionally, the annual demand specifically for the years 2030 and 2035 are plotted in Figure 4.3. These two years are chosen as they are interesting to look at from a critical raw material demand perspective and because the year 2030 is included in demand forecasts by the EU [12]. As most technologies in the smaller segments of commuter and regional aircraft are just introduced around this time, the demand is still low compared to the values reached in 2050. The annual demand of neodymium and dysprosium both see a fourfold increase from 2030 to 2035, as shown in the Figure 4.3.

The cumulative demand of Nd and Dy from 2022 to 2050 is shown in Figure 4.6. For Nd, the median stands at 475 tonnes, whereas for Dy it is 93 tonnes.



(a) Demand of neodymium in 2030 and 2035

(b) Demand of dysprosium in 2030 and 2035

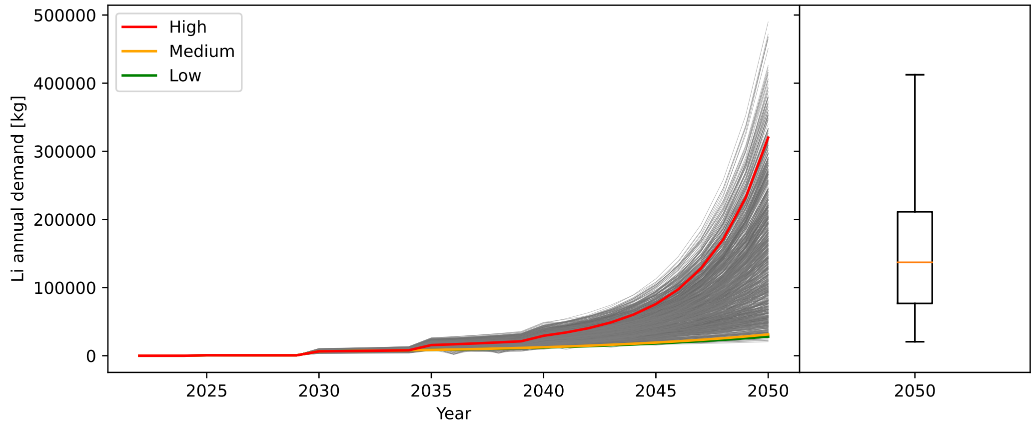
Figure 4.3: Forecast of material demand for electric motors in aviation in 2030 and 2035

4.3.2. Batteries

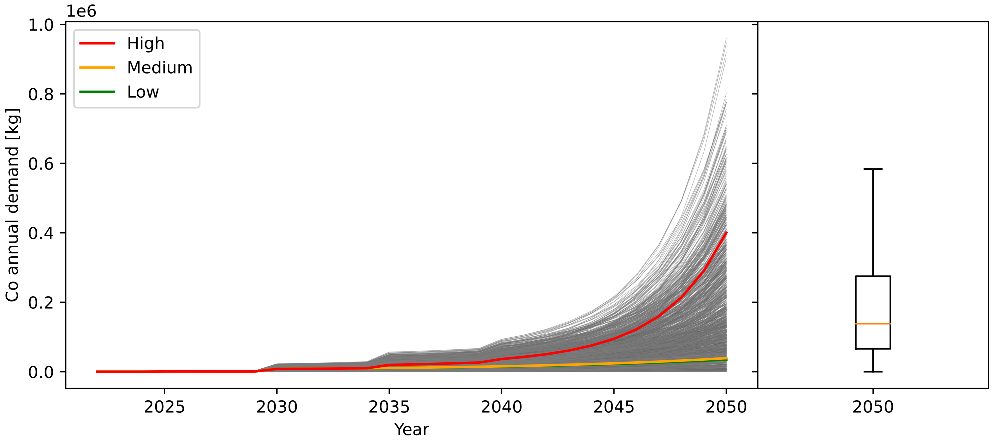
The development of the annual demand for battery-materials lithium and cobalt from 2022 to 2050 is shown in Figure 4.4. Again, the graphs are based on the same simulation with inputs from Table 4.5 and Table 4.6. The first simulation run does not take into account component replacements. Similarly to the electric motor materials, the step-wise increments in the years of commercial introductions of new technologies are also visible. The demand grows significantly beyond 2040, but compared to electric motor materials, rising less steeply.

The material demand for Li in 2050 ranges between 20 tonnes and 400 tonnes, as seen in Figure 4.4a. For Co, this range in 2050 is between no material required, and 800 tonnes of material required, shown in Figure 4.4b.

Here, it is interesting to see that the median of the box plot does not correspond to the medium technology deployment scenario. Both the low and the medium scenario are at the lower side of the graph, even below the lower quartile of the box plot. The high scenario shoots off to higher material demand. From the scenarios themselves in Table 4.4, it is clear that the share of battery-electric and especially hybrid aircraft increases significantly from the low and medium scenarios towards the high scenario, see Table 4.4. This means that the technology development and which market segments are accessed will substantially affect the demand of batteries in aviation. Additionally, the other parameters add a level of variation to the demand forecast. Coincidentally, the median for both Li and Co demand in 2050 is found at 140 tonnes.



(a) Graph for annual demand of lithium from 2022 to 2050, and a box plot of the demand in 2050

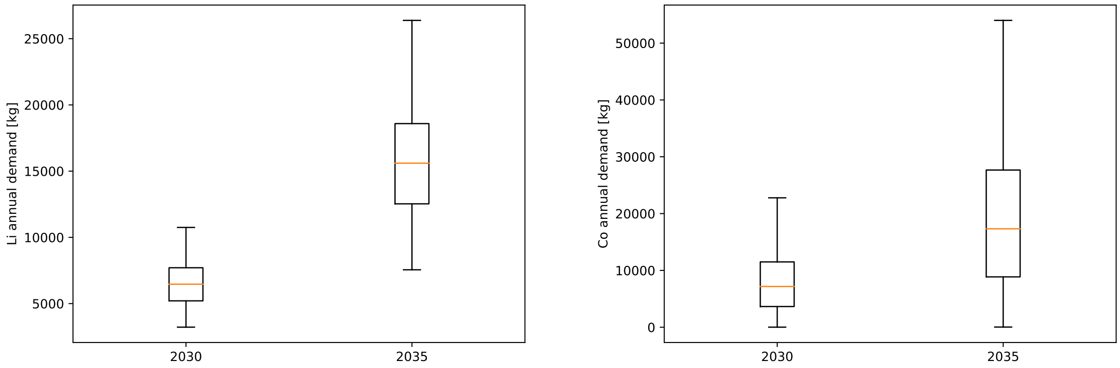


(b) Graph for annual demand of cobalt from 2022 to 2050, and a box plot of the demand in 2050

Figure 4.4: Forecast of annual material demand for electric motors in aviation from 2022 to 2050

Again, the annual demand of Li and Co for the years 2030 and 2035 is shown in Figure 4.5. Relative to the demand in 2050, these two years have a significantly lower demand. From 2030 to 2035, the demand sees a 2.4-time increase.

Figure 4.6 presents the cumulative demand of Li and Co from 2022 to 2050. The median value for Li demand is 803 tonnes. For Co, the median is 955 tonnes. This Figure shows that the battery materials have a much wider uncertainty range than the motor materials.



(a) Demand of lithium in 2030 and 2035

(b) Demand of cobalt in 2030 and 2035

Figure 4.5: Forecast of material demand for electric motors in aviation in 2030 and 2035

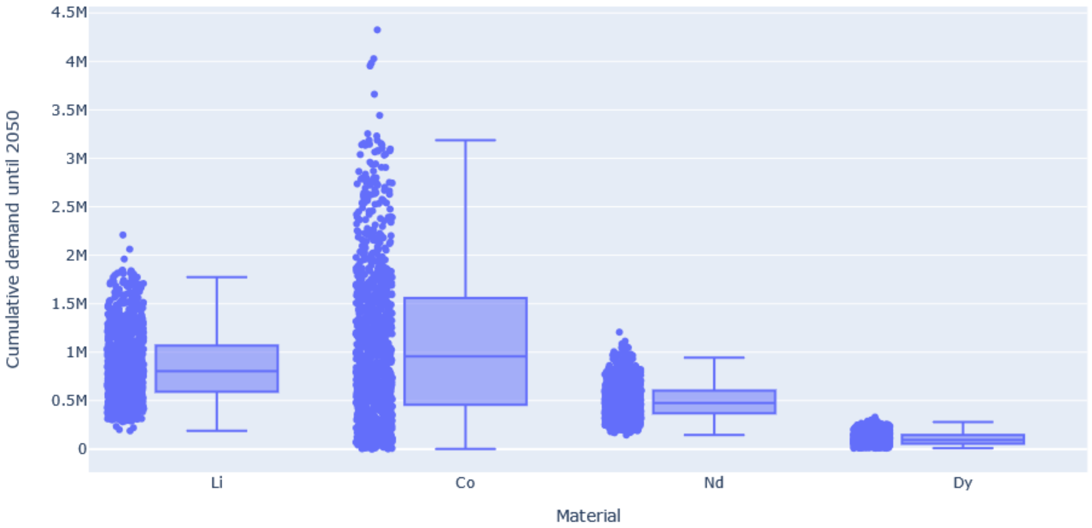


Figure 4.6: Forecast of cumulative material demand of lithium, cobalt, neodymium and dysprosium from 2022 and 2050

4.3.3. Component replacements

The simulation is run again, but now considering how component replacements would affect the material demand in aviation. Electric motors are designed to be operational for approximately 30,000 running hours, which translates to a lifespan of 10-20 years [32]. Here it is estimated that an electric motor will be operational for 15 years. For electric cars, battery lifetimes are reported as 10-15 years [31, 60], depending on the use profile. Research also state that car manufacturers often promise 8-year warranties for the batteries [13, 74]. The battery lifespan is therefore assumed as 8 years in this case. It is also assumed that electric motors and batteries will be changed entirely at the end of this designed lifetime. For batteries this also means that the replacement batteries will have a higher energy density and therefore require less material than the original ones.

The new simulation results are presented in Figure 4.7.

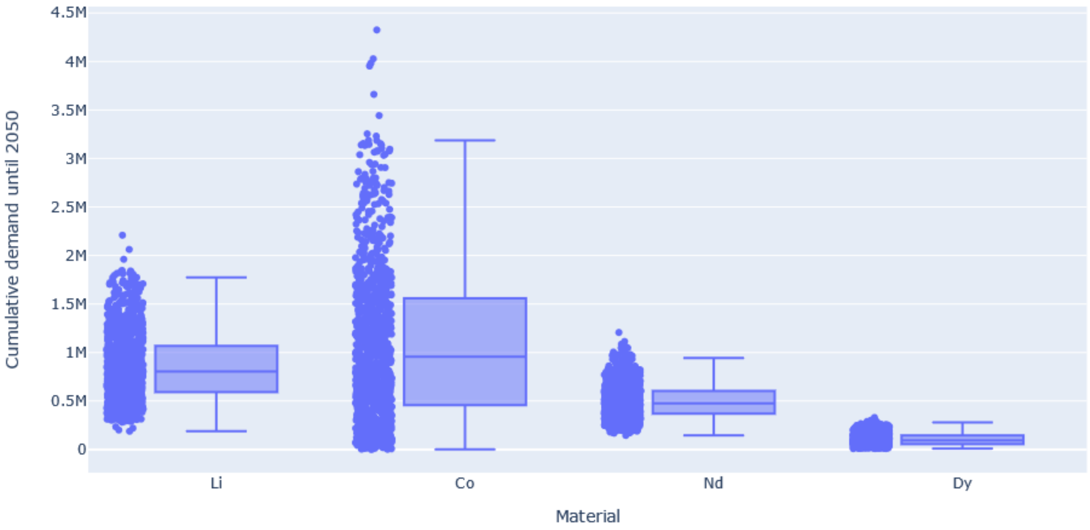


Figure 4.7: Forecast of cumulative material demand of lithium, cobalt, neodymium and dysprosium from 2022 and 2050, including component replacements

The results show that component replacements do not make a significant difference in the material demand by the year 2050. As the material demand for new electric aircraft is mainly increasing after 2040, less material is to replace components of aircraft built before 2040 than to build new aircraft starting from 2040. To quantify the magnitudes, for Nd and Dy, the material demand including component replacements is about 5% higher than the demand computed without any replacements, in the year 2050. For Li and Co, more material is needed for replacements, as the batteries are changed every 8 years as opposed to every 15 years. Li and Co demand goes up by about 15% in 2050.

4.4. Discussion of results

The results show how complex and challenging forecasting future material demand is, especially for a new technology that has not been implemented yet on a commercial level. There is still a lot of uncertainty around the market feasibility of electric aviation, but also on the components applicable for aviation. Most of the parameters used to describe the development of electric aviation are based on assumptions. It is still interesting to compare these results with other material demand forecasts and trends from other sectors.

4.4.1. Aviation material demand

From a first look, one notices the exponential growth rate in material demand in Figures 4.2 and 4.4, especially for the high technology deployment scenario. A constant annual growth rate was assumed for new electric aircraft. Although the assumption might not be exactly the case in reality, such an exponential growth pattern has been the case for electric cars, see Figure 4.8. It is thus not unheard of to see such a breakthrough in adopting new technologies once they have reached commercial maturity. Electric aviation is still in development, and there is no certainty on when exactly it will reach maturity.

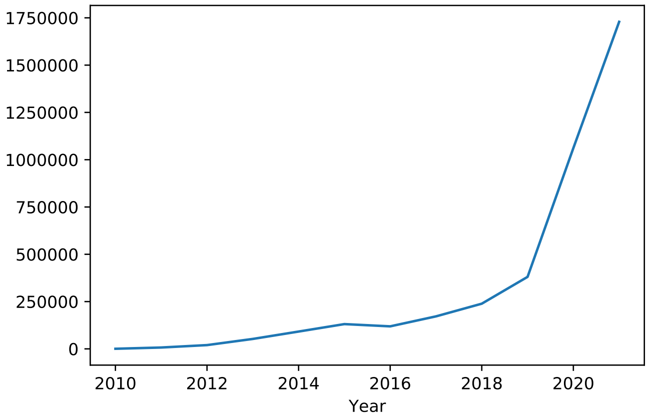


Figure 4.8: New registrations of battery and hybrid electric vehicles in the EU per year[24]

The year of commercialization affects the shape of the curve, thus the annual demand values. The main factor impacting the total material demand is unsurprisingly the percentage of electric technologies in 2050. Motor material demand increases significantly with fuel cell aircraft introduced in the short-range (narrowbody) sector. A major aircraft manufacturer and a developer of fuel cell aircraft, Airbus[25], is also looking into the regional and short-range segments. The latter covers over 50% of the global fleet, making it an important segment for sustainable technologies.

The battery material curves in Figures 4.4a and 4.4b rise less steeply. Two reasons can be identified for this. First, fuel cell aircraft, which are assumed to become more widely adopted after 2035 and 2040, carry electric motors but were assumed not to have batteries. Second, the energy density is assumed to be increasing towards 2050, which means that less battery mass is required per aircraft to reach the same energy. This is a critical assumption that not only impacts the material demand, but also is required to enable flying with batteries onboard. If battery-electric and hybrid aircraft developments stay in the smaller segments, the material demand will stay low (low and medium scenarios), but accessing the short-range (narrowbody) segment will have an enormous impact.

According to the results obtained here, the material demand in aviation is not yet significant in the years 2030 and 2035. It is increasing at a fast rate, but the years between 2040-2050 are more crucial for the aviation sector. In the meanwhile, it is expected that new material compositions are developed, and critical raw material concentration in products could be lowered through material substitution. However, here it is good to note that new technology implementation in aviation is relatively slow, and substituting new materials into parts once certified could be challenging.

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[25] https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe

4.4.2. Demand from other industries

In the wider context of critical raw materials, the commercial aviation sector is rarely considered. Therefore, it is of interest to compare the aviation material demand forecast with other estimates.

The researchers Empl et al. have also modelled the material demand in aviation in the future. They assumed that the future fleet of short- to medium-range aircraft would consist of the electric Ce-Liner type designs [22]. They assumed that in 2035, 5% of the mid-range fleet would be electric aircraft of this type, and that by 2050 this type would cover 80% of the fleet. The results for the material demand obtained by Empl et al. are much higher than the results here, by orders of magnitudes: 129,424 tonnes of neodymium in 2050, 19,414 tonnes of dysprosium, and 427,930 tonnes of lithium (cf. 120 t, 22 t and 137 t). The explanation is that the total share of electric aviation is much higher in the estimations by Empl et al. In this study, electric aircraft are not even considered for medium-sized aircraft. Additionally, battery-electric aircraft are only assumed to be able to reach a 2.4% share of total fleet by 2050 in the medium technology deployment scenario. Even hybrid and fuel cell aircraft are only expected to reach 4.8% and 10.6% shares respectively.

The EU report on critical raw material use across strategic sectors shows predictions for material demand in the renewable energy and e-mobility sectors [12]. The results of the research are compared to the current material demand across all sectors in Table 4.7. It is seen that the predicted annual material demand values for aviation in 2030 and in 2035 do not add significantly to the current annual demands. In 2050, there is a marginal increase to the baseline demand from Nd and Li use in aviation. However, for Dy, the increased use through aviation in 2050 would add a 10% increase in the current Dy demand. Due to the high general demand of cobalt, the consumption from the aviation sector stays negligible.

Critical raw materials are expected to complicate strategic technology implementation, as material demands are expected to exceed the production rates by 2030 [12, 28]. The materials studied here for use in aviation are also present in components for e-mobility applications: electric motors and batteries are used for electric cars. Table 4.7 also compares the modelled demand from the aviation sector to the expected increase in demand through e-mobility applications from the EU forecast [12]. The expected additional demand of Li and Co from e-mobility in the year 2030 and in 2050 exceed the current baseline demand considerably. The share of aviation in this case becomes negligible. For Nd and Dy, electric aviation adds only marginally to the forecasted e-mobility demand. The Nd demand growth is presented visually in Figure 4.9. The results are not surprising, as the aviation sector is much smaller than the e-mobility sector.

Because the model is based on the assumption that electric aviation is only starting to become fully commercially available and mature in 2050, the main outcome of the analysis is that the material demand will therefore stay negligible compared to other sectors until 2050. However, it is important to keep in mind that the general demand for these materials is expected to rise immensely in the meantime, which means that supplies do not suffice to cover the demand. Even though the aviation sector itself has negligible demand, it will experience the same problem as other sectors: it is not known yet how that demand can be met. Additionally, it is important to note that the this demand prediction does not include possible other motors present in aircraft for various other purposes, such as air conditioning and electrification of other systems. The use of electric motors in propulsion systems for aircraft is still relatively new, which means that there are many other challenges to overcome: new certification is needed, new maintenance procedures, and new end-of-life processes.

Table 4.7: Modelled material demand from aviation compared to the combined baseline demand from all sectors within the EU (baseline given in [12]), and to the estimated additional demand from traction motors or e-mobility within the EU (estimated additional demands given in [12]). The numbers given here for aviation are median values, shown in tonnes.

Estimated annual demand	**Year**	**Nd**	**Dy**	**Li**	**Co**
Baseline demand [t] [12]	2023	4000	200	6000	30000
Additional demand from aviation [t]	2030	0.7	0.1	6.5	7.2
	2035	3	0.6	15.6	17.3
	2050	119.7	21.9	137	138.4
Additional demand from e-mobility [t] [12]	2030	1300	410	51000	67000
	2050	3300	1100	130000	110000

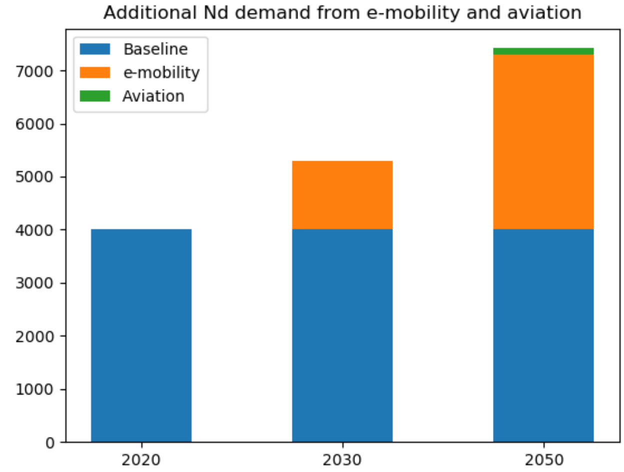

Figure 4.9: Neodymium demand growth: estimated annual demand of Nd in the EU is shown for 2020, 2030 and 2050.

4.4.3. Limitations of the results

The main limitation affecting the results is data availability. Since electric aviation is still in development, there is a lack of information available on the components that can be used and possible end-of-life procedures. Due to the limited data available, the research includes many assumptions, which creates a lot of uncertainty. Verification of the material demand prediction and validation of the results is challenging, as similar models do not exist. Compared to material demand from other sectors in Europe, aviation is still a niche market.

Another limitation of the study conducted is that only commercial aviation segments are included in the demand estimations. General aviation and private business jets are not considered. The general aviation fleet was estimated to consist approximately 440,000 aircraft in 2019 [27]. The aircraft are small, and could potentially be replaced by electric or hybrid aircraft in the future. However, the lifespans of general aviation aircraft vary, the market is not as researched and documented as the commercial aviation sector, and different environmental regulations apply. On the other hand, the business aviation fleet is close to the size of

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[25] https://www.eea.europa.eu/ims/new-registrations-of-electric-vehicles

the commercial aircraft fleet: in 2017, there were approximately 22,000 aircraft [38, 88]. The sizes differ from small, medium to heavy. Most business jets fall under small or medium sizes, but the numbers are not equal in the studies mentioned here [38, 88]. Different sustainable propulsion technologies could be implemented in the business aviation sector. However, the operations and emissions of business aviation are not well researched, thus there is a lack of available data [76]. It has been estimated that the CO2 emissions from general and business aviation together would add up to 1-2% of total CO2 emissions from aviation [5], but no further studies were found to confirm this.

4.4.4. Answering research questions

Here, the results are related to the corresponding research questions. The first subquestion asks: *How will the aviation sector will develop until 2050?* It was already known that there is a lot of uncertainty around the future of aviation, as electric technologies are still in development. Lack of data and uncertainties made this questions challenging. In the end, three different technology deployment scenarios were built for aviation in 2050, as were shown in Table 4.4.

After establishing scenarios for the development of the aviation sector, the second subquestion is considered: *How will the critical raw material demand for aviation develop until 2050?* The two most important factors impacting the critical raw material demand are the technology deployment rate in 2050 and the time of commercialization of the various electric aircraft models. Here, based on the assumptions made, the material demand starts to grow significantly beyond 2045, when all of the technologies have been introduced. Nevertheless, the demand from the aviation sector stays negligible in comparison to the wider material demand. This was to be expected, as other sectors, such as the car industry, are much bigger than the aviation sector.

Although from the results of this study it seems that the aviation sector will only become a minor consumer of electric motors and batteries and their materials, it is still important to consider the supply and demand balance of these materials. Currently, Nd, Dy, Li and Co are listed as critical raw materials, which means that they have high supply risks. Additionally, the demand is expected to increase substantially globally [12]. For Nd and Dy, the demand is expected to exceed current production rates by 2030, and for Li and Co this could happen even sooner [12]. Such imbalance in the supply and demand could lead to competition between sectors, geopolitical tensions, and even limit technology development. The aviation sector especially requires time to switch to new standards, which means that it might be challenging to adopt components from substitute materials. It is important to account for criticality of materials, and to integrate circular strategies in the design to secure material supplies, if possible. In order to answer the main research question and to determine how circular strategies could impact the material demand in aviation, further steps are needed in the research. The next step is to look at component and material performance and to assess the impact of circular end-of-life processes on those.

5

Circular strategies

This chapter focuses on what circular strategies are feasible for electric aviation. First, a general framework is chosen for categorizing end-of-life strategies. Then, the performance requirements for electric motors and the magnets within are described. The feasibility of various end-of-life strategies is evaluated against these requirements. The feasible end-of-life strategies are then fitted into the framework. Finally, a discussion is presented on how the circular strategies could affect the demand of critical raw materials in the aviation sector until 2050.

5.1. Framework for circular strategies

The background for the circular strategies considered in this report is the Resource States Framework developed by Blomsma and Tennant [11]. An adapted version of this framework is visually presented in Figure 5.1. The framework functions as the basis for evaluating circular strategies applicable to electric motors in aviation. This Section gives an overview of the framework and the associated definitions.

5.1.1. Resource States Framework

In this framework an industrial life cycle is built around three states in which resources can exist: particles, parts and products [11], represented in Figure 5.1. The particles state starts from the extraction of materials and continues to the processing of bulk materials. When materials are combined and manufactured further they undergo a resource transformation and become parts. These are then combined in a final assembly into products, the final resource state. Products are distributed to users. In a linear economy, used products are often discarded as waste (not shown in Figure). In a circular economy, the end-of-life products are collected to extend the useful lifetime of the materials. The products can be transformed back into parts through disassembly. After further separation, they can return to the particles state. Between every stage within the product system, some materials can escape from the system. The author has chosen not to visualize these losses in Figure 5.1 in order to simplify the diagram, and to focus more on the circular economy aspect.

The end-of-life options in a product system are presented in Figure 5.1, applying the principles of Blomsma and Tennant [11]. Some end-of-life processes reintroduce the resources back into the system, these are numbers 1-3 shown in orange. These are so-called closed loop strategies. Other processes lead the resources outside the product system, these are the open loop strategies numbered 4-6 in blue. End-of-life processes can take place in any of the three resource states. However, depending on the condition of the product at its end-of-life stage after the first use application, some treatments and strategies could be unfeasible.

In strategies 1 (Direct reuse) and 4 (Alternate use, also known as repurposing), the product is reused as-is, either in the same application or in a different use case. Strategies 2 and 5

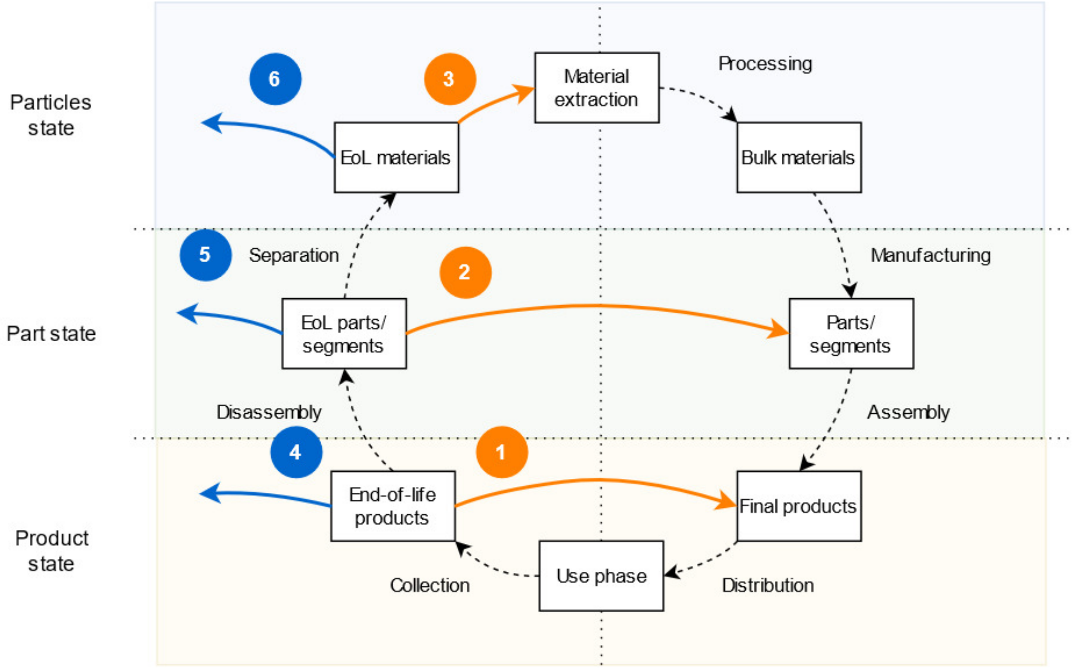

Figure 5.1: Resource States Framework adapted from Blomsma and Tennant [11]. Left side shows the three resource states. The lifecycle phases of a product are marked in blocks and the processes between stages given. The end-of-life routes for the product system are as follows: 1 - Direct reuse, 2 - Part rework (closed loop), 3 - Recycling (closed loop), 4 - Alternate use, 5 - Part rework (open loop), 6 - Recycling (open loop).

(Part rework) take place after disassembly. Here, rework is used as an umbrella term describing repair and remanufacturing activities for a product, but on a part level. The individual parts could be repaired and assembled again to serve in the same product system. This activity can either serve as repair, extending the lifetime of a product, or as remanufacturing, where the product is returned to the same or even better quality as the original manufactured product. Parts can also be removed from the product system. In this case, individual parts are recovered for a different use application as before. The final end-of-life strategies here are 3 and 6, both recycling, in the particles state. Recycling recovers the materials from the product. It is possible that a product directly moves from the product to the particles state. For example, if the product is shredded, there no parts left to recover. The shredded material can still be processed to recover some materials.

5.1.2. Application of the framework

In the context of aviation, the aircraft itself is the final end-product, but due to the complexity of such a system, it is more interesting to consider the sub-assemblies within the aircraft. In electric aviation, an electric motor can be seen as a product. A permanent magnet can then be considered a part of this product, and the Neodymium-Iron-Boron (NdFeB) alloy as a material would be in the particles state. It can be separated even further into the individual materials. Similarly, a battery cell could be considered a product. The cathode, the anode and the electrolyte of a battery are parts, which are composed of material compounds in the particles state.

The opportunities for end-of-life treatment of electric motors in electric aviation are studied in this report. The focus is especially on the NdFeB magnets within the motor, that contain critical raw materials. From the perspective of securing the supplies of such critical raw materials within a sector, it would be beneficial to focus on closed loop strategies. However, as it might be the case that some strategies are impractical for these components, the open loop ones will be included and are discussed on high level.

In this study, the environmental impact of circular strategies is not investigated in detail, but it can be said that in general processes in the product state require less energy and material input than processes in the parts or particles states. Recycling at the particles state has the most significant environmental impact, as it requires the most processing steps, input energy and input material.

However, the reuse of a product is not always preferred from an environmental perspective. In some cases, technological advancements mean that newer products consume less in their use phase than older ones. In such situations, replacing the old product with a newer one is preferred. In this report, all circular strategies are compared from perspective of the product, part, or a material meeting the engineering requirements. For recycling processes, the focus is on material quality. In future work, it is recommended to take the environmental impact of the various end-of-life routes into account.

Similarly to the environmental impact, the economic feasibility of end-of-life strategies is outside the scope of this research. The costs of processing products, parts and materials are not assessed. Again, in general, it can be said that less processing steps will have lower costs. Hence, reuse of products is likely to be the least costly option, but it does not mean that the market for reused products would be more easily accessible than that for recycled materials. Economic aspects are important for large-scale implementation of different end-of-life routes and it is recommended that these are investigated in the future.

Here, electric motors are chosen as the case study, with the focus on NdFeb magnets. The end-of-life strategies for batteries in electric aviation are also interesting for future research.

5.2. Performance requirements

In order to establish what end-of-life strategies are feasible for electric motors in aviation specifically, the required performance of this component needs to be determined. Here, the requirements of the motor itself and the magnet within are investigated.

5.2.1. Electric motor performance

The main design parameter for electric motors in aviation is the specific power (power per unit mass) [29, 93]. The specific power of the motor is affected by the magnetic loading, the electric loading, the electrical frequency, the rotor tip speed and the current density [93]. However, all of these are limited by physical constraints, such as magnetic properties of the material, joule losses or cooling capacity [93]. In most cases, increasing one parameter will have an adverse effect on the other values. Therefore, the design will require a trade-off between the parameters. The maximum power density of electric motors reaches roughly 5 kW/kg, typically achieving about 2.5 kW/kg, compared to modern turbofans, which can reach a specific power of 10 kW/kg [29].

As electric aviation is not yet commercially adopted, there is limited information available on the performance of electric motors for aviation or the magnets used in the motors. In Table 5.1, existing products from industrial manufacturers are presented. The electric motors by Pipistrel, EMRAX and Siemens include permanent magnets, but the grades of the magnets are not listed. The magnets considered by NASA for electric motors are shown on the Table.

Table 5.1: Magnet properties for given electric motor performance from reference aircraft. Specific power is taken as the peak motor power at maximum load. The maximum temperature is given for the magnets specifically, unless it marked with a star, in which case it is given for the electric motors.

Developer	Magnet grade	Specific power [kW/kg]	Max temp. [C]	Remanence [T]	Coercivity [kA/m]	Energy product [kJ/m3]	Source
Pipistrel	-	2.54	110*	-	-	-	Pipistrel[1]
EMRAX	-	4.43	120	-	-	-	EMRAX[2]
Siemens	-	5.90	90*	-	-	-	Siemens[3]
NASA X-57	N48H	5.64	120	1.39	1046	378	NASA [34]
NASA X-57	N50H	-	120	1.42	1066	390	NASA [34]
NASA X-57	N48SH	-	150	1.39	995	374	NASA [34]
NASA Sceptor	N45SH	3.83	150	1.32-1.37	979-1070	342-358	NASA [19], CES [30]

The specific powers of the Siemens motor and NASA X-57 design are at the high end of motor performance with values above 5 kW/kg. The EMRAX motor also has a high specific power at 4.43 kW/kg. The NASA design for Sceptor has a lower specific power, but still above average. Out of the motors studied here, only the Pipistrel one has about average performance.

5.2.2. Certification considerations

Additionally, the regulatory requirements for electric motors have only been introduced recently. The existing certifications specifications for aircraft engines do not consider electric and or hybrid propulsion systems [20]. Therefore, the European Aviation Safety Agency has issued a Special Condition to support certification of electric and hybrid propulsion systems. It provides general certification requirements for electric propulsion systems, focused on testing and proving safe operations of the total system, regardless of the architecture [20]. For this reason, it does not specify acceptable design values, architectures or materials used. The Special Condition intends to link the certification requirements of the propulsion system to those of the overall aircraft [20]. The Means of Compliance are defined for different system architectures and types of aircraft [20].

Another point of consideration for this research is the certification of reused and recycled parts. According to a report by ICAO [21], 85-90 percent of the weight of a retired aircraft is either reused or recycled. Here, no distinction is made between the different types of components: electric and electronic equipment, structural parts, interior, etc. It would be interesting to further study which parts are reused in the aviation sector. In order to loop disassembled parts back into the aviation sector, they need to retain their airworthiness status, or they have to be recertified [21]. As there is still limited documentation for the certification of electric motors and for reuse and recycling activities in general, it is expected that standards and regulations for the reuse and recycling of such components will only be developed later.

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[1] https://www.pipistrel-aircraft.com/products/other-products/e-811/

[2] https://emrax.com/wp-content/uploads/2020/03/manual_for_emrax_motors_version_5.4.pdf

[3] https://www.bbaa.de/fileadmin/user_upload/02-preis/02-02-preistraeger/newsletter-2019/02-2019-09/02_Siemens_Anton.pdf

5.2.3. Neodymium–Iron–Boron magnet properties

NdFeB permanent magnets are some of the strongest magnets available. The magnetic properties of NdFeB magnets originate from their microstructure [14], as discussed in Chapter 2. In Table 5.1 four different magnet grades are considered for electric motors in aviation. All of the magnets are produced via sintering. The magnet grades considered are of the higher end of NdFeB magnets, showing high remanence, coercivity and energy density values.

From the maximum operating temperature values shown in the Table it can be seen that the magnets need to be able to continue operations in at least 90 degrees, and preferably withstand even higher temperatures. The maximum operating temperature values for the Pipistrel and Siemens motors are for the motors themselves, whereas the other values shown are for the magnets.

It is interesting to point out, that magnets have much longer lifespans that electric motors: the lifespan of electric motors is about 10-20 years [32], whereas NdFeB magnets are in theory permanent, but they tend to deteriorate due to exposure to high temperatures and corrosion [40].

5.2.4. Requirements for aviation

From the small data set presented in Table 5.1 no definitive conclusions can be drawn regarding the requirements for the permanent magnets used in electric motors for aviation. Additionally, no correlation can be made between the magnet grade and the achievable specific power performance of the motor. As the motor performance also depends on other factors, such as the cooling system, this was to be expected. Nevertheless, it can be assumed that only high grade NdFeB magnets will be considered for aviation applications. The lowest magnet grade used in the studied reference systems is N45SH, thus this can be assumed as the minimum required performance for magnets in electric motors in aviation.

Based on this information the maximum operating temperature for the magnet is assumed to be 120 degrees. The lowest remanence and coercivity values come from the grade N45 magnet. The assumptions for the required magnetic properties are summarized in Table 5.2.

Table 5.2: Required magnet performance and the corresponding minimum properties.

Required grade	Max temperature [C]	Remanence [T]	Coercivity [kA/m]	Energy product [kJ/m3]
N45H/N45SH	120	1.32	979	342

5.3. Results for end-of-life routes

The applicability of different end-of-life strategies for electric motors is studied here. The performance and the quality of components and materials supplied from secondary sources should still meet the requirements established above. Special attention is put on the NdFeB magnets, which contain critical raw materials neodymium and dysprosium.

5.3.1. Reuse

Electric motor lifetimes are usually counted in operating hours. Most electric motors can operate around 20,000-30,000 hours, which, depending on the use case leads to a lifetime of about 10-20 years [32]. After this time, components of the motor start failing. Most common causes of failure are the bearings and the windings [80]. If the motor is used in an aircraft for the full estimated lifetime, it is unlikely that the motor would be fit for direct reuse or alternate use (repurposing). Usually, motor failures cannot be repaired without disassembly of the motor into its constituent parts.

Magnet lifetimes can be higher than motor lifetimes, if operated below the maximum temperature conditions and not exposed to corrosion [40]. Currently, there are no commercial end-of-life recovery strategies in place for permanent magnets within products [86]. Many electric components with permanent magnets are discarded as a whole, they are considered waste as they reach the end of their life. The magnet lifetimes are therefore often reported based on the product lives: consumer electronics only span 2-3 years, whereas wind turbines have lifetimes of 20-30 years [58]. Magnets as individual parts however could be reused due to longer lifetimes.

5.3.2. Rework

For many motors, the useful lifetime could be significantly increased by reworking parts: remanufacturing into a new equivalent product and repairing parts enough to extend the lifetime [80]. Both processes start with disassembly and inspection of the parts [80]. When the failed components are identified, these can be replaced. After repairs are conducted and the parts tested, the motor is assembled again and tested for functionality. Most common parts that need replacements are bearings and windings. Rotors and stators should be inspected for damage in the air gap surfaces and in the laminations. Permanent magnets in the rotors can be reused directly if they are not damaged in the disassembly process. Repairs can extend the lifetime of a motor, but after remanufacturing, the service life of the motor should be in line with that of a newly built equivalent motor [80].

Remanufacturing and repairing of electric motors is thus feasible and the magnets can be reused in remanufactured and repaired motors. Parts can be thus reworked into the same product system, but they could also be salvaged for other systems. The reuse of magnets for different systems is more challenging in case the motors are disassembled and the parts separated [18]. Many motors have very specific requirements for the magnet shape and performance, depending on the use application [18].

5.4. Results for recycling processes

The goal is to investigate which recycling methods would be suitable end-of-life strategies for NdFeB magnets in electric aviation, if any. The material requirements identified in Section 5.2 will act as the base performance against which recycled materials are compared. The recycling routes assessed can be divided into three main categories: pyrometallurgy, hydrometallurgy and magnet-to-magnet recycling [18].

The first two can be considered material extraction methods: the REEs are recovered, usually in an oxide form, which can be further processed into the metallic form [25]. Pyro- and hydrometallurgical recycling is available for all types of magnet waste [86]. For example, electrical and electronic waste is often shredded, which means that the magnets are not separated from other materials. Such shredded waste material is only suitable for REE recycling via extraction. On the other hand, magnet-to-magnet recycling methods are only suitable for pure, large waste magnets [25, 58, 86]. In these methods, the REEs are not extracted from the alloy, but the alloy is reworked directly into a new magnet.

5.4.1. Hydro- and pyrometallurgical recycling

In pyrometallurgy, the REEs in magnets are separated from other materials by converting them to another phase [86]. They require high temperatures, and therefore also high energy inputs [58, 86]. The main processes can be divided into roasting, liquid metal extraction, molten salt extraction, molten slag extraction and electrochemical processing. However, most of the processes are only applicable to concentrated production waste, and not for the recycling of end-of-life magnet waste [86]. Molten slag extraction could be used to recycle shredded waste material, if followed by some hydrometallurgical processing [86].

The main hydrometallurgical steps are leaching the waste material, separation of individual REEs, precipitation, and conversion to oxides [86]. One of the main difficulties is separating the individual REEs from one another, due to their similar physical and chemical properties [25, 86]. Hydrometallurgical recycling consumes non-recoverable chemicals and creates various waste streams [58, 86]. Even Fe and B residues are discarded as waste, because the cost of recycling Fe is not economically competitive and because B can be hazardous to the environment [25].

In general, hydro- and pyrometallurgical processing routes are environmentally unfavourable in comparison to magnet-to-magnet recycling [18, 25, 58, 64, 86]. Pyrometallurgical steps energy intensive and hydrometallurgical processing uses many toxic chemicals. These recycling routes have not been scaled up commercially, quantity of recovered elements does not cover the processing cost [64]. Nevertheless, these recycling routes are identified as the most feasible recycling route for low grade magnets or possibly even contaminated waste streams, to at least recover the valuable REEs. A combination of hydro- and pyrometallurgical methods is required for treating waste magnets [25, 86].

These methods are suitable for REE recovery from magnets in electric motors. The recovery of elements over alloys suggests that the RE oxide matches the quality of primary material. These methods are hence not studied in more detail at this stage.

5.4.2. Magnet-to-magnet recycling

Magnet-to-magnet recycling means recycling the alloy without separating and extracting materials. The methods include 1. hydrogen decrepitation (HD) and resintering, 2. hydrogen disproportionation desorption and recombination (HDDR), 3. recasting and melt spinning [40, 86]. Recasting poses some difficulties: magnets usually contain adhesives or coatings that affect the purity of the product, and some REEs are lost in the process [41]. HDDR process is also reported to reduce the remanence of the recycled magnets so much, that they are suggested to be used to produce bonded magnets [59]. Both HDDR and melt spinning are better suited for the production resin-bonded magnets [40, 73, 86], but high-performance electric motors require strong sintered magnets with high remanence [48]. Thus, the most promising method left is resintering with hydrogen decrepitation.

Recycling through hydrogen decrepitation follows similar processing steps as primary magnet production [72], see Figure 2.5 in Chapter 2. Waste magnets are processed into powders that are resintered into magnets. One of the advantages of this method is that multiple recycling cycles are possible [72, 89]. In order to evaluate the applicability of HD to magnets for high-performance motors, literature on experimental data is collected from other researchers. Nine experiments from researchers were studied. The results from the experiments are summarized in Table 5.3.

Table 5.3: Summary of the results from experiments in magnet recycling through hydrogen decrepitation. Further notes: ^{a} Data points read from a graph; ^{b} Tested values obtained at 80 degrees instead of room temperature; ^{c} Material tested in powder form, further processing to magnet needed.

Sample	Addition	Remanence [T]	Coercivity [kA/m]	Energy product [kJ/m3]	Density [g/cm3]	Source
Starting material	N/A	1.18	870	260	7.56	Zakotnik & Williams [89]
1st cycle	none	1.18	695	260	7.39	
2nd cycle	none	1.08	575	216	6.86	
3rd cycle	none	1.08	536	215	6.8	
4th cycle	none	1.05	343	146	6.7	
2nd cycle	1.0 at.% Nd hydride	1.20^a	715^a	270^a	7.5^a	
Starting material	N/A	1.26	1255	285	-	Li et al. (2014) [42]
1st cycle	none	1.22^a	875^a	262^a	-	
1st cycle	0.5 wt.% NdDyCoCuFe	1.23	890	264	-	
1st cycle	1.0 wt.% NdDyCoCuFe	1.23	990	263	-	
1st cycle	2.0 wt.% NdDyCoCuFe	1.23	1150	266	-	
1st cycle	3.0 wt.% NdDyCoCuFe	1.21	1290	264	-	
Starting material	N/A	1.45	810	394	-	Zakotnik & Tudor [90]
1st cycle	1.0 at.% Nd,Pr	1.42	1041	390	-	
Starting material	N/A	1.37	1032	352	-	
1st cycle	0.5 at.% NdDyCoCuFe	1.37	1310	366	-	
Starting material	N/A	1.37	1032	352	-	
1st cycle	2.0 at.% NdDyCoCuFe	1.33	1662	345	-	
Starting material	N/A	1.37	1032	352	-	
1st cycle	3.0 at.% NdDyCoCuFe	1.29	1876	323	-	
Starting material	N/A	1.25	1874	295	-	Li et al. (2015) [44]
1st cycle	24.0 wt.% NdPrFeB	1.24	1980	291	7.56	
Starting material	N/A	1.37	1037	-	7.55	Sepehri-Amin et al. [73]
1st cycle	5.0 wt.% NdDyCoCuFe	1.29	1883	-	7.55	
Starting material	N/A	1.11	1838	243^b	7.71	Diehl et al. [18]
1st cycle	none	1.04	1561	206^b	7.51	
1st cycle	2.0 wt.% Nd hydride	1.04	1699	206^b	7.56	
1st cycle	4.0 wt.% Nd hydride	1.01	1480	194^b	7.56	
1st cycle	6.0 wt.% Nd hydride	0.99	1365	188^b	7.58	
Starting material	N/A	1.40	943	355	-	Michalski et al. [52]
1st cycle	none	1.10^c	497^c	121^c	-	
1st cycle (hybrid)	none	1.15^c	434^c	109^c	-	
Starting material	N/A	1.38	1080	369	7.58	Schonfeldt et al. [72]
1st cycle	none	1.29	1147	314	7.36	
2nd cycle	none	1.21	1015	273	7.17	
1st cycle	2.0 wt.% Nd hydride	1.27	1146	309	7.47	
2nd cycle	2.0 wt.% Nd hydride	1.19	1132	268	7.23	
3rd cycle	2.0 wt.% Nd hydride	1.18	1098	258	7.35	
1st cycle	4.0 wt.% Nd hydride	1.27	1118	310	7.56	
1st cycle	6.0 wt.% Nd hydride	1.24	1214	295	7.54	

Feedstock of waste magnets for recycling

In order to compare the results of the experiments to the requirements in aviation, a few important aspects need to be considered: the grades of the waste magnets used in the experiments, the batch sizes for recycling and the coatings on waste magnets. All of these are important for assessing the applicability of the recycling process to aviation, as the waste magnets in the experiments are not directly comparable to waste magnets from the electric motors in aviation. All nine experiments used actual waste magnets from end-of-life applications. The waste magnet feedstocks varied from hard disk drives to MRI scan machines. The batch sizes tested for the HD recycling process also differ. All of these are listed in Table 5.4.

Table 5.4: Summary of the feedstock for the experiments. Further notes: [a] Batch size for coating removal 300kg, for hydrogen decrepitation 120kg; [b] Magnets recycled without any preprocessing or treatments applied before hydrogen decrepitation.

Feedstock	**Grade**	**Batch size**	**Coating type**	**Coating removal**	**Source**
Hard disk drives	-	10g	Nickel	Fracturing and peeling	Zakotnik & Williams [89]
-	35H	-	none	none	Li et al (2014) [42]
Multiple sources: MRI machines, WEEE	-	300kg/120kg[a]	-	Steel shot blasting and acid bath	Zakotnik & Tudor [90]
-	35SH	500kg	Nickel	Peeling	Li et al. (2015) [44]
Multiple sources: MRI machines, WEEE	-	100kg	Nickel, Zn, Al	Steel shot blasting	Sepehri-Amin et al. [73]
Electric motors	-	-	-	-	Diehl et al. text
Hard disk drives	-	20g	Nickel	not removed[b]	Michalski et al. [52]
MRI	-	10.6kg	not disclosed	Sand blasting	Schonfeldt et al. [72]
MRI	-	100kg	not disclosed	Steel shot blasting	Prosperi et al. [64]

Most experiments do not report the grades of the waste magnets. In the studies by Li et al. (2014) [42] and Li et al. (2015) [44], the recycled waste magnets are lower grades than those that are assumed to be required for aviation, as seen in Table 5.4. From the properties shown in Table 5.3, it seems that only the waste magnets in the study of Sepehri-Amin et al. [73] and Schonfeldt et al. [72] meet the requirements assumed for aviation.

The batch sizes for recycling are listed in Table 5.4. According to the assumptions made in Chapter 4, an electric motor would need approximately 0.014 kg magnet material per kW output. Based on this, commuter aircraft would need about 20 kg of magnet material, regional 125 kg and short-range 285 kg material. The larger batch sizes listed in Table 5.4 are comparable to waste magnets that could be recovered from electric motors in aviation. Thus, technically it is feasible to recycle a magnet of the size used in an electric motor in aviation. Of course, recycling becomes more economical with larger batch sizes, which could be magnitudes higher.

Lastly, most magnets use corrosion-resistant Nickel coatings. These are removed through different processes, as shown in Table 5.4. Remains of coating materials could contribute to contaminants in the recyclate. In the experiment by Michalski et al., the researchers do not pre-process the waste magnets [52]. The damaged coating is left in place. The impact on the impurities and properties of the recycled magnets will be discussed next.

An important note is that all the experiments considered seemed to receive waste material from one type of magnet source, or if there are different waste sources, the properties of the materials are known. If magnet recycling will take place in a large scale, the quality of the source material could become a problem. The properties of the waste material are not always known, and waste composed of magnets with varying compositions and properties could lead to different results as the ones seen here.

Impact of recycling on material composition

The experiments have slightly different processing parameters for hydrogenation and dehydrogenation: the temperature, time, and pressure at which hydrogen is admitted vary. The reader is referred to the original scientific publications for specific data on processing. Similarly, milling parameters vary, and the compacting is conducted at different pressures. Finally, sintering is also performed at slightly different temperatures and durations. Some experiments blend in new REE-based material, the material additions can be seen in Table 5.3.

An important note in the processing is that more oxygen is introduced in the material through oxidation of REEs at the grain boundaries [44, 90]. The grain boundary will not fully melt in the sintering phase to the presence of these oxides which have higher melting points [18, 86]. This means that it is not possible to achieve full density for the recyclate. Diehl et al. suggest that the density can be recovered better by mixing in Nd hydride material [18]. Researchers also highlight that further improvements of density can be reached by optimizing the sintering process [18, 72]. The optimal sintering and annealing parameters change with the material composition and should be determined for every individual batch [18, 72]. Due to contamination, the composition of the material changes, which means that the optimal processing parameters also change. Schonfeldt et al. conclude that the optimal sintering temperature and sintering time increase after every processing cycle [72]. In addition to oxygen, other contaminants will also enter the material during recycling. Carbon is introduced in various stages: as other material residues are removed before processing, and as the green compacts are aligned [90]. The coating of the waste magnets is the main source of contamination in the recycling process [90].

Impurities and porosity

The researchers found that without any additives, the volume fraction of the Nd-rich phase decreases and that the original volume fraction of the Nd-rich GB cannot be reached [42]. The share of Nd in the alloy composition is decreasing, and the Nd-rich grain boundary phase is diminishing [89]. The cause for this reduction is contamination. For magnets recycled without additions, an increase in impurities is reported: the oxygen and carbon contents increase significantly [72, 89]. Schonfeldt et al. also note an increase in the nitrogen content [72]. The presence of contamination leads to increased porosity in the microstructure of recycled magnets [72]. This is visualised in Figure 5.4 by Zakotnik and Williams [89] and Figure 5.2 by Schonfeldt et al. [72]. It is noted that the porosity increases after every recycling cycle, leading to lowered density for the recycled magnet[89].

However, the porosity is reduced when additives are blended in during the recycling process [72, 89]. Reduced porosity also leads to increased density of the recycled material. When new Nd-rich material is blended in, the grain boundaries are modified. The Nd-rich phases are concentrated at the grain boundaries, and the Nd-containing additives increase the volume fraction of the grain boundary phase [44, 72, 73]. Additionally, a Dy-rich shell is also formed around the outer edges of the grains [73]. Such changes in the grains and grain boundaries are noted to improve the density and the coercivity of the recycled magnet [73].

Figure 5.2 shows the differences in the microstructure for recycled magnets without Nd hydride addition and with the addition [72]. The difference in porosity is notable: they are reduced when additives are blended in. Similarly the Nd-rich grain boundaries are more prevalent with additives. The microstructures of the recycled magnets from the experiment of Zakotnik and Williams without additions and with neodymium hydride are shown in Figures 5.4 and 5.5 [89]. It becomes clear from the figures that porosity is higher for magnets without added Nd hydride.

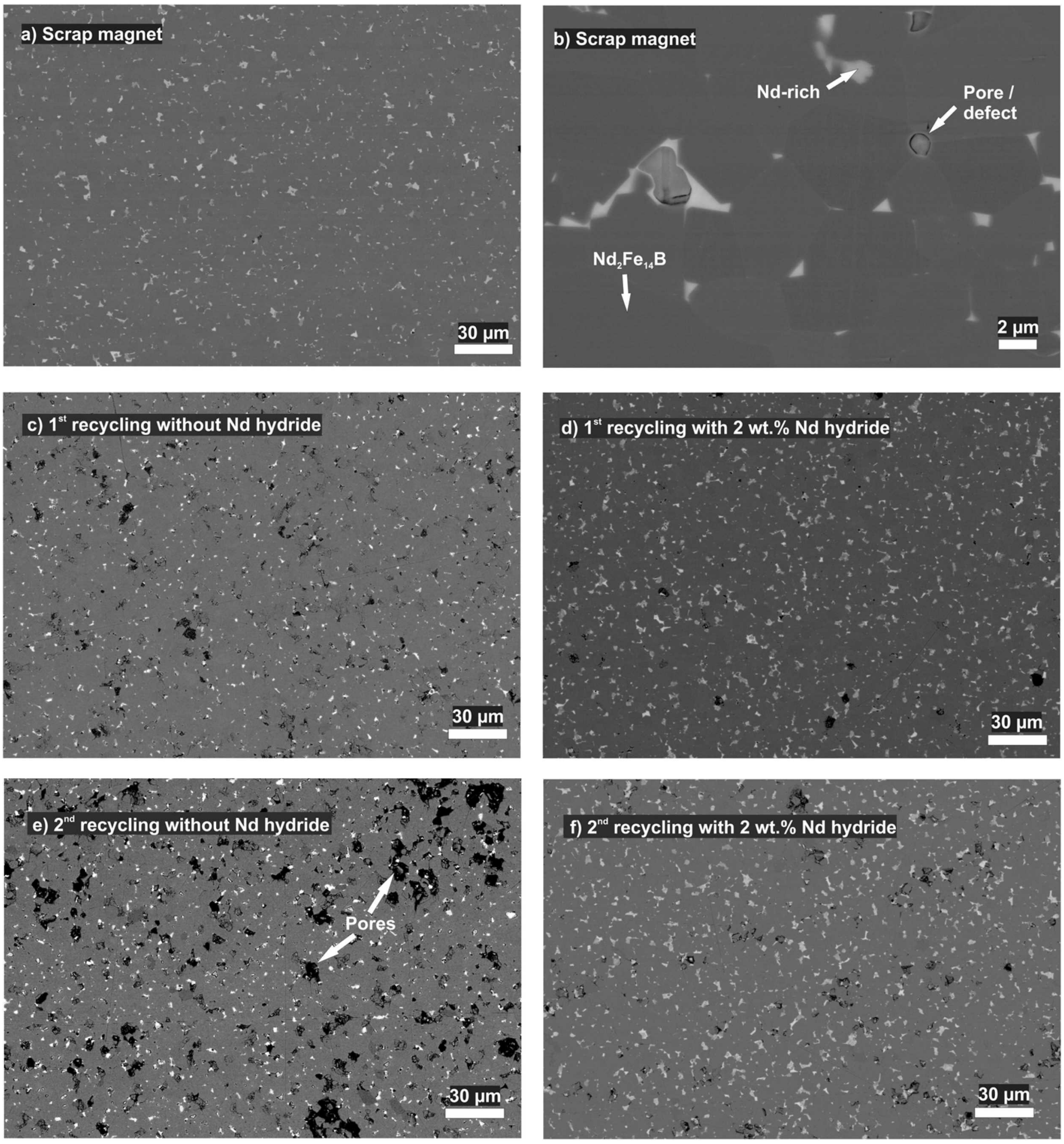

Figure 5.2: Microstructure of recycled magnets with and without 2 wt.% Nd hydride additions from Schonfeldt et al. [72]. The grey area is matrix material Nd2Fe14B, the light areas are the Nd-rich grain boundary phases, and the dark grey areas show porosity.

Similarly, the reduction of the Nd-rich grain boundary phase (light colour) is clear, compared to the blended magnets.

Li et al. found a peak in the achievable density when 2 wt.% of additive content was mixed in [42]. At higher shares of additive, cracks start to form along the grain boundaries, leading to a decrease in density. It is suggested that the cracks were formed due to the presence of some residual hydrogen from the additive. During sintering, this residual hydrogen was likely released, creating cracks [42].

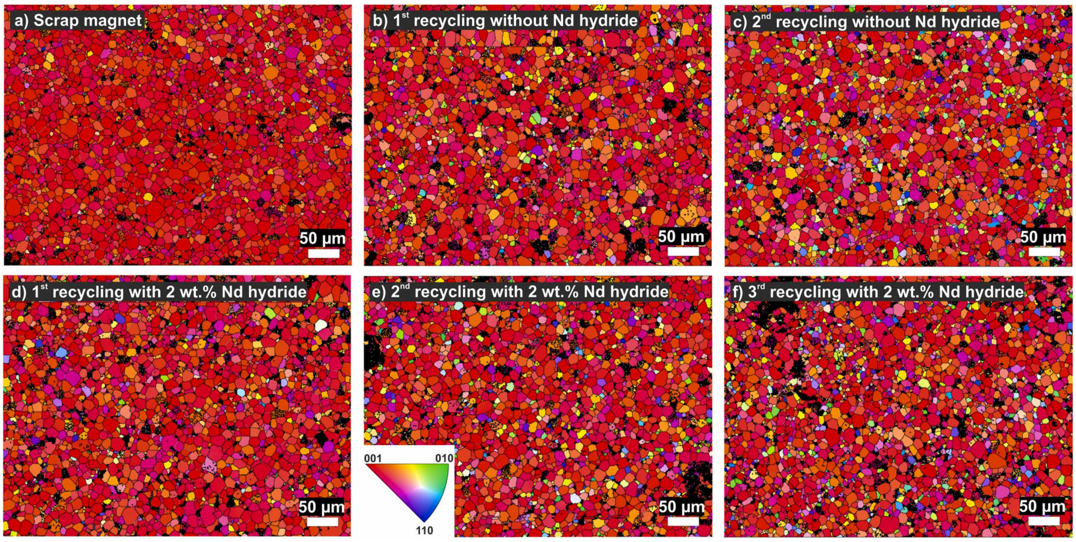

Figure 5.3: Magnetization direction map from Schonfeldt et al. [72]. Grains aligned with the sample z axis direction are coloured red, and misalignment is shown in other colours. Misalignment increases with increasing number of recycling cycles.

Recycling impact on remanence and coercivity

The magnetic properties of the recycled magnets do not reach the values of the scrap magnets (see Table 5.3. From the results of the experiments studied here, it can be said that coercivity can be recovered better than the remanence.

Schonfeldt et al. conclude that unblended magnets exhibit lower remanence than ones with additives [72]. However, even magnets with Nd hydride addition show lower remanence values than the starting scrap magnet. The researchers suggest that this is caused by the increasing share of Nd-rich grain boundary phase, which would lead to a reduction in the share of main magnetic matrix phase [72]. Similar statement is made by Li et al. (2015) [44]. Recycling also causes misalignment of grains with respect to the magnetization direction, which lowers the remanence. The misalignment is visualized in Figure 5.3. Specifically in the experiment conducted by Schonfeldt et al., it is mentioned that a higher remanence could be achieved by changing the processing route: usually isostatic pressing is used for high grade magnets, but the researchers produced the recycled magnets with transversal field pressing [72]. Diehl et al. note, that due to the recycling process, Dy atoms substitute Nd atoms in the matrix phase, which leads to grains with higher magnetic anisotropy. Hence, resulting in lower remanence but higher coercivity [18].

Coercivity can be recovered through the addition of new Nd-rich material. The blended magnets show constant or even increased coercivity, see Table 5.3. According to Schonfeldt et al. [72] and Li et al. (2015) [44], the Nd-rich grain boundary phase resulting from the addition of Nd hydride magnetically decouples grains, which increases the coercivity. Yet, simultaneously the addition of new material also has the opposite effect: these magnets are denser and have less pores than the unblended ones, which strengthens the coupling of the grains [72]. For unblended magnets, the magnetic decoupling due to increased porosity could explain the increase in coercivity after the first recycling cycle in the experiment of Schonfeldt et al. [72]. After this, the changes in the microstructure become so substantial that the properties are reduced [72].

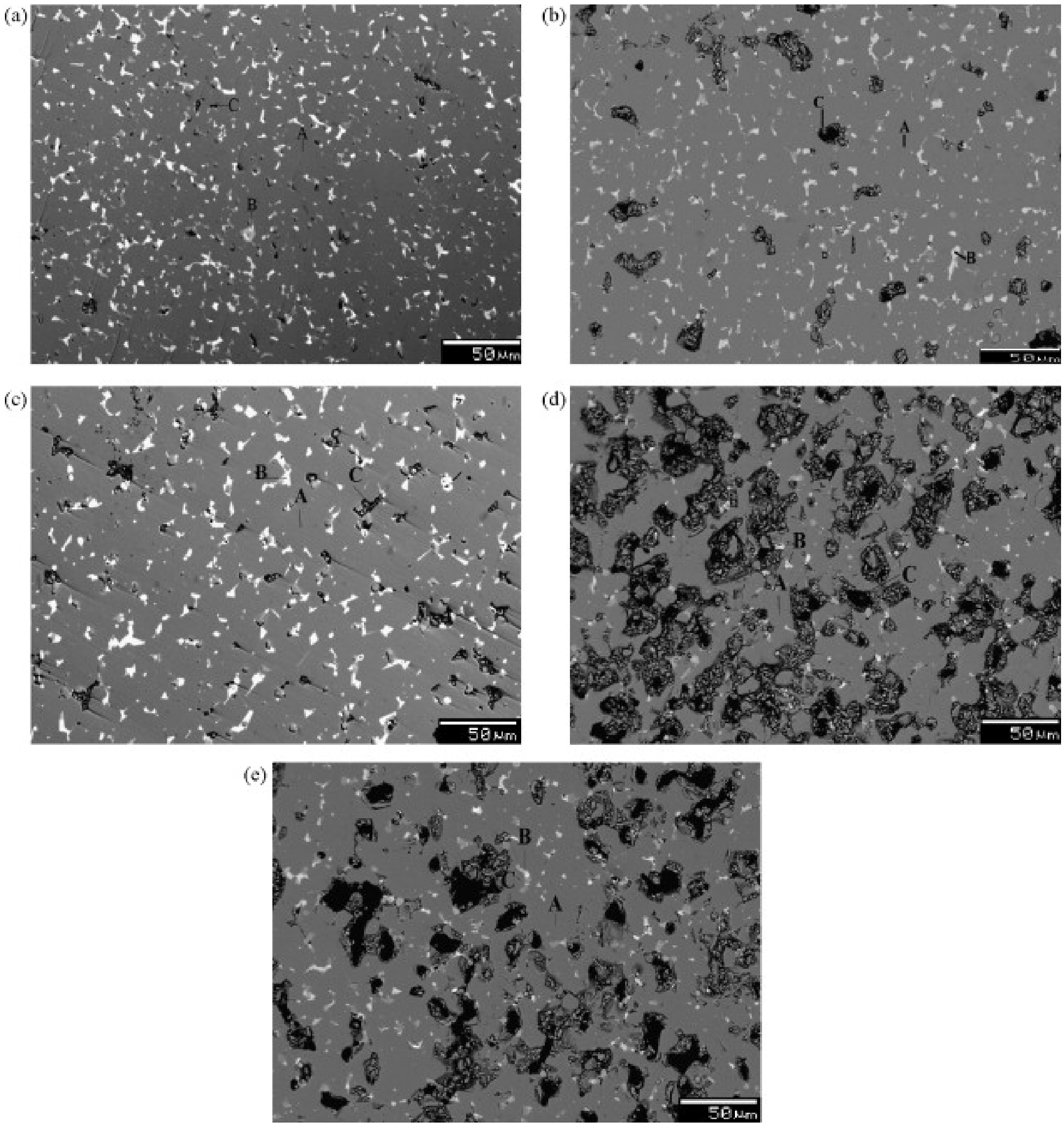

Figure 5.4: Microstructure of recycled magnets without additions: (a) starting material, (b) 1st cycle, (c) 2nd cycle, (d) 3rd cycle, (e) 4th cycle, from Zakotnik et al. [89]. The grey area is matrix material Nd2Fe14B (A), the light areas are the Nd-rich grain boundary phases (B), and the dark grey areas show porosity (C).

In the study by Li et al. (2014), remanence is recovered to about 97% of the original and it starts to decrease further if more than 2 wt.% new material is added [42]. However, the coercivity can be recovered with higher shares of additives, and it even exceeds the original at 3 wt.% [42]. Without additives, the recycled magnets were found to lose 6% in remanence and 15% in coercivity in the experiment of Diehl et al. [18]. Nd hydride addition restores the coercivity, and even increases it in comparison to the scrap magnet [18]. However, further increase in the Nd hydride addition is found to eventually reduce the coercivity. Here, the best magnetic properties were achieved with 2 wt.% Nd hydride [18].

In the experiment by Li et al. (2015), the researchers were able to restore 99.20% of the remanence, 105.65% of the coercivity and 98.65% of the max energy product [44]. Such a

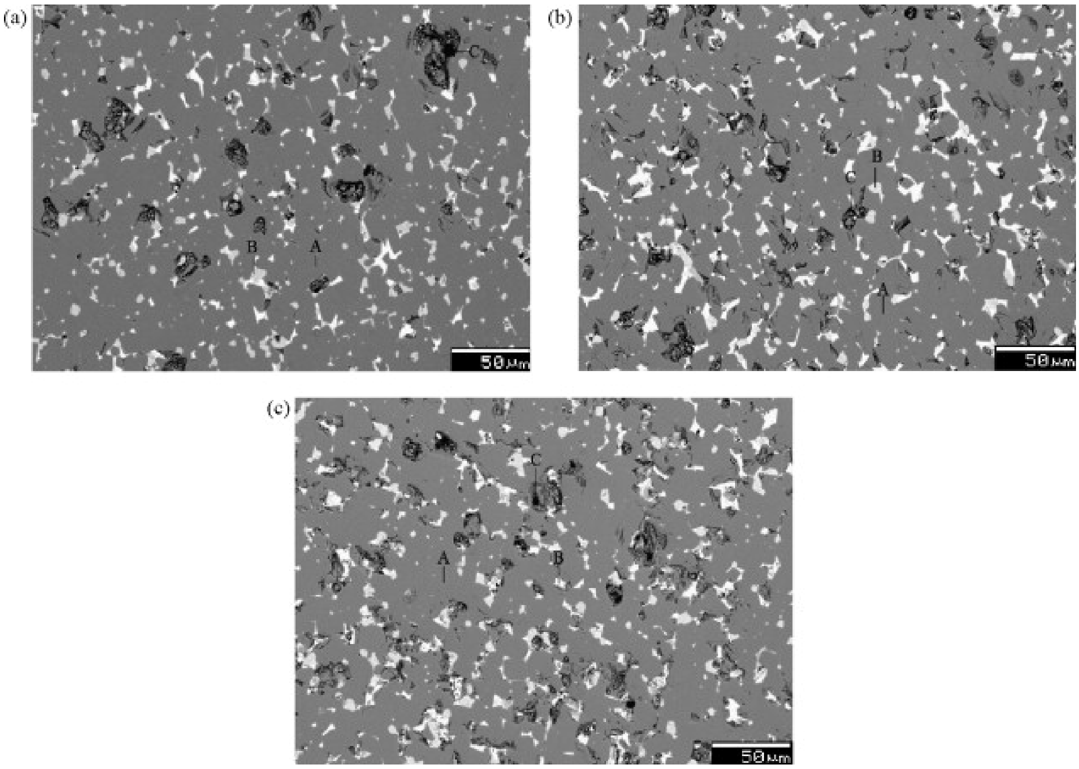

Figure 5.5: Microstructure of recycled magnets with 1 at.% Nd hydride added during 2nd, 3rd, and 4th cycle: (a) 2nd cycle, (b) 3rd cycle, and (c) 4th cycle, from Zakotnik et al. [89]. The grey area is matrix material Nd2Fe14B (A), the light areas are the Nd-rich grain boundary phases (B), and the dark grey areas show porosity (C).

high recovery rate of properties is suggested to be better than in any other study.

Michalski et al. recycled untreated waste magnets without removing the damaged coatings. The researchers tested different temperatures and pressures for the hydrogen decrepitation step to see how it would affect the properties [52]. The impact of temperature on the material properties was unclear, but it was found that the lower pressure led to improved properties. It is mentioned that processing the waste material in low temperature and pressure preserves the microstructure better than high temperature and pressure. Michalski et al. suspected that oxidation could take place between the hydrogenation and dehydrogenation steps [52]. Therefore, the researchers also developed and tested a hybrid process with a combined hydrogenation and dehydrogenation cycle. From Table 5.3 it can be seen that hybrid process did not lead to significantly improved properties compared to the separate processing steps. Further studies could be conducted on this aspect. It is also noted that high refinement during the processing increases the coercivity, but at the same time lowers the remanence, both due to finer particle sizes. The researchers suggest that the magnetic properties of the recycled powders would be suitable for further processing into resin-bonded magnets instead of sintered magnets [52].

Prosperi et al. compare the performance of two electric motors, one with magnets made from primary materials and one with magnets produced via the magnet-to-magnet recycling route, specifically via the trademarked m2m process [64]. The researchers conclude that the properties of recycled materials can be recovered and even improved, if new REE-based material is added to the alloy during magnet-to-magnet recycling. In this case, the researchers added a rare-earth rich alloy to the waste magnet material. However, the article does not disclose how the properties of the magnet material were affected by the recycling process. No information is available on the properties of the waste magnets before recycling. It is also not mentioned if the waste magnets were of the same grade as the primary magnets tested in the motor. The compositions of the primary magnets and the recycled magnets differed slightly: the recycled magnet had a higher Nd content and a lower Dy content.

5.4.3. Barriers against recycling

Although materials used in permanent magnets are considered critical, and their demand is growing, recycling of permanent magnets is not conducted on a large commercial scale yet [86]. End-of-life recycling input rate (EoL-RIR) for LREEs in the EU is 3% and for HREEs 8% [10]. For neodymium specifically the EoL-RIR in the EU is 1% and for dysprosium 0% [10]. There are many barriers to the implementation of recycling. It is important to investigate the challenges, as some might be product-specific, and some related to the materials themselves. With this information, it is possible to evaluate how the aviation sector is affected.

Dismantling of products is often done manually [68, 80]. Magnets are relatively brittle and can therefore be easily damaged in the disassembly [80]. Recovery of magnets is also challenging when the magnets are small or embedded within the part [68, 90]. In electric motors, magnets can be placed inside the rotor (known as interior permanent magnets). Additionally, magnets are often attached to the surrounding components with strong adhesives [68].

The chemical compositions of magnets vary greatly, and when a product reaches its end-of-life, there is often little to no information available about the magnet composition [25, 68, 80]. Different chemical compositions also require adjusting the processing parameters for recycling treatment [18].

The lack of technical knowledge of magnet production and recycling in Europe is also mentioned as a barrier [68]. European policies have identified the importance of critical raw materials for the economy, and there is a push towards sourcing materials from within Europe [10, 12]. From literature studied for this report, it becomes clear that there is wide research interest towards recycling magnets, as secondary sourcing of material is both more environmentally friendly and less dependent on geopolitics. However, Europe is lacking practical capabilities in this front, as most of the magnet materials are supplied from outside the EU.

Lastly, recycling is not yet economically competitive with primary source materials [25, 58, 64, 86]. This is partially due to the low concentrations of REEs in for example waste from electrical and electronic equipment [24, 86]. Many recycling processes are energy- and labour-intensive, and only recover limited quantities of valuable REEs [64, 86]. The recycling processes are not technically mature yet, especially for treating large batches of waste stream material with variable compositions [25, 86].

5.5. Discussion of results

Based on the experimental results presented, the feasibility of recycling magnets is discussed. After this, all of the circular strategies found feasible for electric motors in aviation are combined into the Resource States Framework. On particles and part state the focus is on NdFeB magnets containing critical raw materials. Lastly, the implications of circularity on the raw material demand is considered, leading to an answer for the main research questions.

5.5.1. Recycling of magnets in aviation

Reuse and remanufacturing strategies are preferred over recycling from an environmental perspective. Recycling is also less advantageous from an economic viewpoint, since more input work and materials are required. Yet, recycling is the only possible option when magnets are reaching their end-of-life and are no longer serving their functional purpose. Recycling might also be the only possibility when reuse and remanufacturing are not economically feasible for example due to difficulty of separating magnets from the waste stream.

Out of the three main types of recycling methods applicable for sintered NdFeB magnets, hydro- and pyrometallurgical methods are possible for the magnets used in electric aviation. These methods can be used to extract the critical and costly rare-earth elements, Nd and Dy. However, they are not the preferred end-of-life strategy, since they only recover the REEs and waste other materials. Additionally, their environmental impact is significant: they are energy-intensive processes with possible toxic chemical waste. From a technical perspective, the materials recovered through a combination of hydro- and pyrometallurgical means can be re-entered into the same product system, thus reworked into magnets for aircraft motors. The REEs could also be used for other products.

Magnet-to-magnet recycling would be a preferred route over pyro- and hydrometallurgical methods, as here the magnet alloy is processed as a whole, without extracting individual materials. Based on the data from experiments conducted, it seems that magnet-to-magnet recycling via hydrogen decrepitation could be feasible for magnets in electric aviation. However, there are limitations.

It seems to be unlikely, that the properties of the recycled magnet could still meet the requirements without an addition of new material during the recycling process. For aviation applications, one would preferably have both a high remanence and a high coercivity. The properties of the recycled magnet can be improved by modifying the grain boundaries. In practice this happens by blending in Nd hydride or another material that includes REEs.

The recycling process affects the coercivity of the magnet through two opposing mechanisms: coupling and decoupling of grains. For recycled materials with new material blended in, the new Nd-rich grain boundary will magnetically decouple the grains and thereby increase the coercivity. Simultaneously, the material is becoming denser and a reduction in porosity is seen. Porosity comes from contamination and impacts coercivity in two ways. Pores can separate grains from each other, creating a decoupling effect. Yet, the pores can also function as nucleation sites for demagnetization, as domain walls can move across the grains. The results from the experiments show that excessive porosity reduces the coercivity significantly, as is the case for materials recycled without any addition of material. For such materials, the fraction of the magnetic matrix phase reduces, and the high porosity and lowered density drop the coercivity.

Remanence cannot be recovered as well as coercivity with the addition of new material. The recycled materials suffer from impurities and contamination, which affect the alloy composition. An increase in oxygen content is seen due to oxidation, and additionally remainders of the coatings can introduce contaminants. The volume share of magnetic matrix material is reduced. During recycling some of the Nd atoms in the matrix phase are also replaced by Dy atoms. With optimized processing steps, it is likely that a remanence close to the original one can be reached. However, this poses the main challenge: for every change in alloy composition, processing parameters need to be changed.

An important note is that all the experiments considered seemed to receive waste material from one type of magnet source, or at least recycled waste magnets with known properties. If magnet recycling will take place in a large scale, the quality of the source material could become a problem. Waste composed of magnets with varying compositions and properties could lead to different results as the ones seen here.

The main limitation of the recycling assessment here is that it is based on literature and not primary data from experiments. All of the results reported here are dependent on the experimental conditions of the other researchers. Further experiments could be conducted to validate the results on larger batches of end-of-life material of the grade interesting for the aviation sector. The required remanence and coercivity will also depend on other motor parameters.

Furthermore, the properties of the magnet material decrease at every recycling cycle, thus it is not possible to recycle magnets via the hydrogen decrepitation process indefinitely. From the experimental values in Table 5.3 it can be seen that the properties are already significantly reduced after the second recycling cycle, thus the magnets could potentially only be recycled once with this method. Magnet-to-magnet recycling still has an advantage: most processing steps are already used in primary production of magnets, even grain boundary diffusion, which can ease the implementation of this recycling process.

5.5.2. Circular strategies framework for electric motors

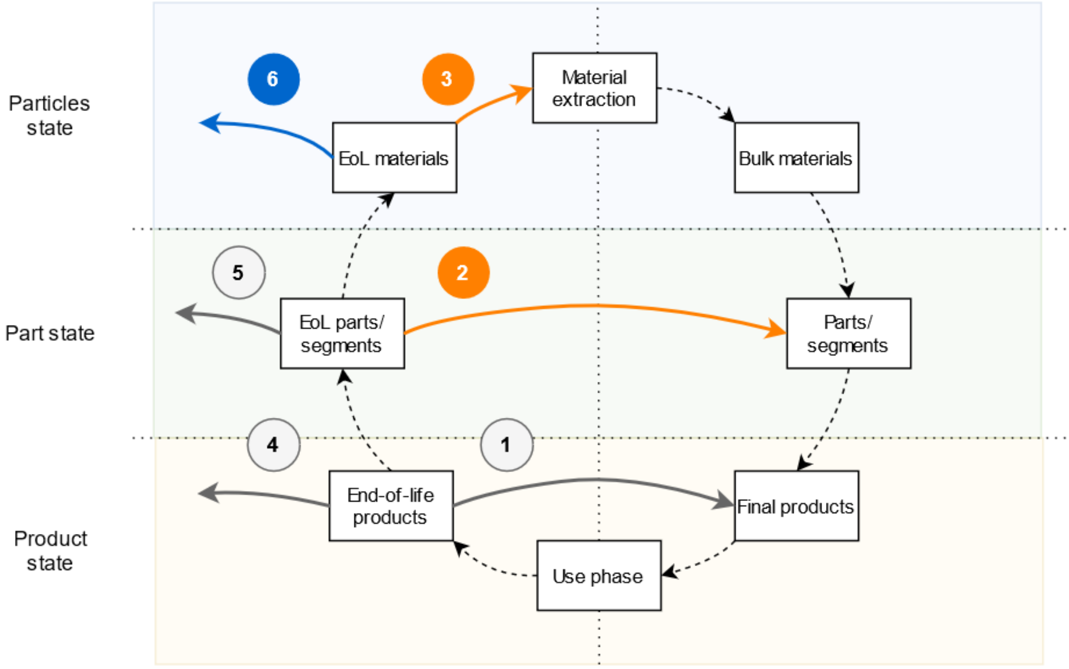

Figure 5.6: Results of the circular strategy assessment for permanent magnet electric motors in aviation implemented in the Resource States Framework by Blomsma and Tennant [11]. In the part and particle state, the focus is on the NdFeB magnets within the electric motor. Other electric motor parts are not considered.

Finally, by combining the information of all the results in this section, it is possible to establish which circular strategies are applicable to end-of-life electric motors in aviation. The results can be presented in the Resource States Framework, shown in Figure 5.6. The product system is taken as an electric motor used in aviation, but with a focus on the NdFeB magnet as a part and the REEs as materials. Figure 5.7 shows the possible end-of-life routes from the perspective of magnets.

Reuse strategies (1 and 4) are not found to be feasible for electric motors in aviation, as motors have limited lifetimes and are not able to perform their required functions anymore after this time. They are thus marked in grey.

Rework of parts is possible for motors. Motor lifetimes could be extended by repairing individual parts. Motors can also be remanufactured, which means that they are reworked back into original quality or even improved quality, with similar service lives as newly manufactured motors. Reworked parts from motors in aviation could also be recovered for other purposes and applications, which means that for such parts strategy 5 is possible. The magnets as individual parts within electric motors usually be directly reused back into the product system, shown in both Figure 5.6 and Figure 5.7 as strategy 2. However, due to different requirements for different motors, it is unlikely that the magnets as parts could be used in other applications. Rework of parts to external systems is not considered feasible.

For recycling of motors (3 and 6), out of all the materials, only NdFeB magnets are considered in this report. It was found that magnets can be recycled as an alloy through a hydrogen decrepitation process. If some REE-based additive material is blended in during recycling, the magnet alloy can be introduced back into the product system. However, this method is only applicable if the waste batch has comparable properties and compositions. The method is still limited to one recycling cycle. Without blending in new material, the properties of the alloy are reduced so much that it is no longer suited for the same application. In this case, the alloy could be used for a different use application. Hydro- and pyrometallurgical recycling is possible to recover only the REEs from the magnets. It is suggested that this could be done after the magnets are fully exhausted. The recovered elements are suitable for any application.

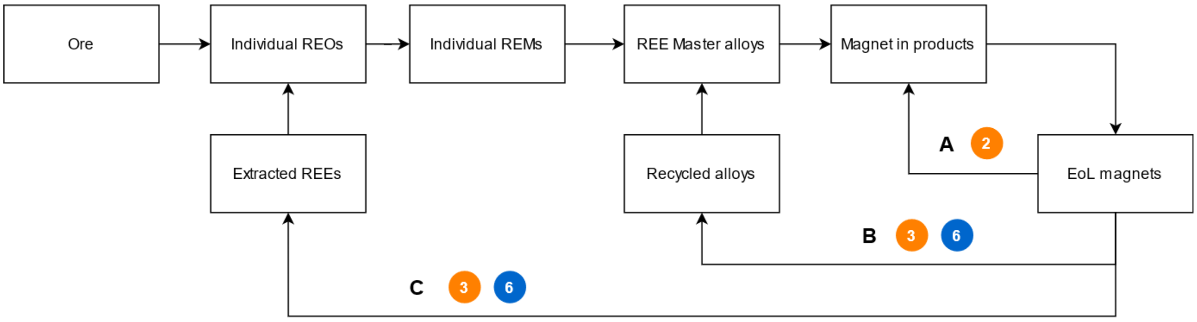

Figure 5.7: End-of-life routes for magnets in electric motors combined with the results of the circular strategy assessment. REO stands for Rare Earth Oxides, REM for Rare Earth Metals and REE for Rare Earth Elements. The end-of-life route map is adapted from Firdaus et al. [25]

5.5.3. Supplying secondary materials

There are existing studies that consider how circular strategies could supply Nd in the US [48] and in the EU [81].

Maani et al. estimated the Nd demand in the US across various applications and evaluated how circular strategies for NdFeB magnets could support that demand [48]. According to the study, the projected Nd demand for electric vehicles in the US reaches almost 6,000 tonnes by 2050. This is almost double the demand that the EU has estimated (3,300 tonnes) [12]. Electric vehicles are seen as the most significant use application of REE magnets [48]. The researchers concluded that reuse of Nd-containing magnets could meet about 70% of the material demand for electric vehicles in 2050. Recycling at a 15% efficiency could meet 12% of the demand in 2050. Here, only closed loop strategies are considered.

Filippas et al. estimated that only up to 5% of the Nd and Dy demand for electric and hybrid vehicles could be supplied through secondary materials from end-of-life vehicles by 2030 [24]. Across all sectors, the researchers conclude that only 0.34-3.9% of Nd and Dy demand could be supplied from recycling. The researchers expect Nd and Dy demands to exceed production rates in 2026 and 2021 respectively [24].

From the circular strategies that are deemed applicable for NdFeB magnets in aviation applications, magnet reuse could allow for remanufacturing of electric motors. However, it is difficult to reuse the magnets in alternative product systems due to different requirements in terms of shape and performance [18], which could also become a challenge within the aviation sector, if the motor designs differ between manufacturers. If end-of-life materials in aviation are recycled in batches with consistent material properties, magnet-to-magnet recycling is possible. Otherwise, magnets can be recycled back to their elements through pyro- and hydrometallurgical methods.

One of the identified challenges for using secondary material source is that products and applications that currently contain high concentrations of REE magnets have long lifetimes [48]. It means that resources will take a long time to become available for supporting the demand growth. Researchers van Nielen et al. pinpoint a different aspect of the same challenge in their study, stating that due to high demand growth, the potential secondary supply cannot fully meet the high Nd demand [81].

Based on the material demand prediction, it also seems to be the case for aviation. The products that reach their end-of-life before 2040 will not be able to significantly supply the required components and materials to aircraft built after 2040, as the demand is increasing exponentially. The recycling rates predicted for electric vehicles seem too optimistic for aviation: 5% recycling input rate by 2030, 12% by 2050. The circular economy strategies that can be implemented in the aviation sector will not make a significant impact to the material demand by 2050. Closed loop strategies for secondary material supplies are not enough to cover the material demand.

5.5.4. Open loop strategies

The material demand in aviation could also be supplied by reusing components and recycling end-of-life materials from other applications, as long as they meet the performance requirements of the aviation sector. Similarly, circular open loop strategies can also be applied end-of-life electric motors and magnets from aviation: remanufactured motors as products could be used in other applications, and as shown in Figure 5.7, magnets can be recycled into other sectors. By implementing open loop strategies, the secondary critical raw materials no longer ensure that the demand of the sectoral application is met. However, on a wider economic scale, such as on an EU level, the security of raw material supplies is still improved [23].

In order to assess which secondary applications are feasible for end-of-life magnets from aviation, performance requirements from other applications need to be investigated. It is known that permanent magnets can be used for motors and generators in the automotive sector and in wind energy applications. Further use cases for permanent magnets include various electronic equipment such hard disk drives [16]. Additionally, REE neodymium itself is also used in various other applications, such as metal alloys and ceramics [10].

The magnets used in wind energy are much bigger than the ones in electric motors [57] and also require high grades, even N46 [45]. It is unlikely that recycled magnets from aviation would be directly usable in the wind energy industry. The magnets should be recycled in large, high-quality batches, and have exceptional performance after the recycling process.

In the automotive industry, the grades vary: at least the use of N34, N35, N42, N45 and N54 grades has been evaluated [49, 87, 92]. The magnets in automotive applications need to be operational in high temperatures, up to 150 degrees [57]. It is possible that recycled magnets could be used in the automotive sector. Since the material demand in this industry is much higher than in aviation, it could be of interest to consider open loop strategies and to align recycling practices.

Recycled magnets can also be used in electronic equipment, if the performance requirements are lower than those in aviation. Lastly, if the individual REEs are recovered through hydro- and pyrometallurgical processes, the materials can be used wherever needed.

5.5.5. Limitations of the results

One of the main limitation of the results presented here is that this research only focuses on the technical requirements on the components and materials, neglecting environmental, social, and economic aspects. In order to recommend best possible end-of-life routes for electric motors or any other components, the other aspects should also be taken into account.

Additionally, the results presented here could be validated by experimental testing. The chosen circular strategies should be applied to end-of-life motors and magnets, and the secondary products, parts and materials then tested in aviation applications.

5.5.6. Answering research questions

The feasibility of different circular strategies can only be assessed, if the performance requirements for the components and the materials are established first. Therefore, subquestion 3 is formulated as: *What requirements apply to the components in aviation?* As expected, high performance electric motors are considered for aviation, and the magnets within also need to be of a high grade, quite likely above N45SH.

Now, the fourth subquestion can be answered: *Which end-of-life processes are feasible for the components and materials in aviation?* Here, only electric motors and NdFeB magnets within were investigated. Direct reuse and repurposing of electric motors without any inspections or repairs is not deemed feasible, because they will be retired at the end of their designed lifetime. Remanufacturing of motors is possible. The magnet lifetimes are longer than motors lifetimes, which means that other parts can be repaired and changed, and the magnets can be used further. Looking at the magnets specifically, these cannot be transferred to a different product, but they could be recycled for further use. Magnets can be recycled via hydrogen decrepitation, if further material is added to the alloy. Otherwise, the critical rare earth elements can be recovered through hydro- and pyrometallurgical recycling.

Finally, the main research question is considered: *What circular economy strategies could be implemented to reduce the demand of critical raw materials in electric aviation by 2050?* Combining all the information, it is unlikely that material demand in aviation could be supplied through end-of-life components within the sector itself before the year 2050. Most electric technologies are assumed to become commercial after the year 2030, as described in Section 4.2. Electric motors have lifetimes of about 10-20 years, averaging around 15 years. Most of the motors for the electric aircraft built before 2050 should still be functional at that time.

However, as aircraft lifetimes are usually 30 years, motor replacements will be needed eventually. The number of replacements needed will also become more significant beyond 2050, as will the demand for new motors. Then, motors could be remanufactured or the magnets from old motors recycled for further use.

6

Conclusions and recommendations

This final chapter summarizes the main outcomes of the research. First, the conclusions are presented. Second, recommendations for future research are given. These are based on the conclusions and the limitations of the research.

6.1. Conclusions

This research aims to assess what circular economy strategies could be implemented in electric aviation to reduce the critical raw material demand. Electric motors and the permanent magnets containing critical Rare-Earth Elements neodymium and dysprosium are chosen as a case study. It is concluded that the feasible circular end-of-life strategies, remanufacturing of motors and recycling of magnets, would have limited impact on the demand of primary critical raw materials in the aviation sector by 2050. The commercialization of electric aviation is assumed to start in 2030, and higher deployment rates are only achieved after 2040 or even 2050. Since electric motors have lifetimes of about 15 years, the few motors that reach their end-of-life by 2050 will not contribute much to reducing the primary material demand.

The material demand was modelled for electric motor materials neodymium and dysprosium, and battery materials lithium and cobalt. Due to limited data and high uncertainties regarding the technological developments of the aviation sector, assumptions were made for the deployment rates of electric aircraft in 2050. As could be expected, the technology deployment scenario is the most important parameter impacting the total demand: for all four materials in 2050, the difference in demand changes by approximately a factor of five between the low and high scenario. The results are thus highly uncertain and dependent on the assumptions made. However, it should be noted, that the demand from aviation is still negligible compared to the demand from other sectors in Europe.

Although the material demand in aviation is low in a wider industrial context, it is still of interest to incorporate circularity in the component design. Circular end-of-life strategies can reduce the environmental burden of the components and secure material supplies. Recycling is also a key component of European policy on critical raw materials. In order to assess the feasibility of various strategies to electric motors and their permanent magnets, the required performance of the components was studied. Only high-performance motors and high grade magnets (N45H and above) are considered suitable for aviation. Motors can be remanufactured at their end-of-life, as their original performance is regained through this process. Magnets can be recycled through hydrogen decrepitation, if additional material is blended in with the alloy to recover the magnetic properties. The remanence might not reach the original value, but it can still meet the performance requirements. The coercivity can even improve through the addition of material. Lastly, critical raw materials can be recovered through hydro- and pyrometallurgical recycling of magnets.

6.2. Recommendations

Based on the results and the limitations of the research, further recommendations can be made. First, the research could be extended to include general aviation aircraft and business jets. For now, only commercial aviation was included. It would be interesting to compare the demand results obtained now with a wider research scope including those segments. General aviation and business jets include aircraft of smaller sizes, which means that the technologies studied here are also applicable to those. The business aviation fleet is of similar size as the commercial fleet, which indicates that the material demand could increase significantly, if electric technologies are implemented there.

Similarly, the research could be extended to further components and materials. Only electric motors and NdFeB magnets were included in the circular strategy assessment due to limited time and resources. A similar approach could be used to assess for example batteries and the critical raw materials lithium and cobalt. However, as the material demand between the years 2045 and 2050 is predicted to be much higher than the demand before that, similar results could be expected. Most likely only limited demand could be supplied through materials from end-of-life batteries by 2050.

For the assessment of applicable end-of-life strategies, the research only considers the technical performance requirements of materials. This approach has its limitations. Since the materials and components are not yet widely adopted in aviation, assumptions are made for the required performance. Additionally, the environmental and economic feasibility of the end-of-life processes are not studied. It is recommended to include these in future research in order to gain a more holistic view on the circular strategies and their implications.

Lastly, possibilities in cross-sectoral circular material use could be studied further. Open loop strategies support sustainable material use and can still secure material supplies in a certain region. In order to implement circular economy principles for electric motors, permanent magnets, and the critical raw materials within, a cross-sectoral roadmap could be built to evaluate feasible routes for reuse, rework and recycling. Such a roadmap could help identify connection points and stages where materials are potentially lost. A circular economy can only be achieved, if different sectors and all stakeholders collaborate.

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