ESSENTIAL RAW MATERIALS
FOR THE ELECTRIFICATION OF AIRCRAFT

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Abstract

Power train electrification of ground vehicles is an important and politically advocated avenue to pursue towards independence from fossil resources and reduction of CO_2 emissions. Recently, effort has also been expended on the increased electrification of aircraft, including the future possibility of electric aircraft propulsion. In the present paper some of the essential future technologies for the electrification of aircraft are identified, based on the pre-conceptional short-haul aircraft “Ce-Liner” that was developed at Bauhaus Luftfahrt. Essential raw materials necessary for the realization of these technologies in aviation are assessed with regard to their projected future demand in 2035, the Ce-Liner’s supposed year of entry into service, and in 2050. The result is a first estimate for the amount of essential “electric” raw materials to manufacture these aircraft. The material examples considered here are lithium for advanced energy storage in batteries, neodymium and dysprosium for permanent magnets in highly efficient electric motors for aircraft propulsion and, as an alternative to neodymium and dysprosium, yttrium, required for superconducting electrical components. The present results indicate that, although the future demand for these materials is extensively increased, their supply might be sufficient for aviation. Restrictions in the availability of raw materials are therefore no barrier in the realization of universally electric aircraft.

1. INTRODUCTION

Increasing prices and the price volatility of raw materials in the last decade have raised concerns about shortages in supply of so-called “critical” raw materials. The term “criticality” when employed with respect to raw materials originates from evaluations in the context of national policies [1] (sometimes the term “strategic material”, which relates to the military provenience, is used with the same meaning [2]). Today, ”critical materials” refer to the examination of available material resources with importance to specific technologies, industry branches, countries, regions or the world.
Consequently, raw materials that have been classified as “critical” are economically important raw materials (for a certain industry, for a country etc.) with a risk of supply interruption. Geochemical scarcity of the material (the depletion of reserves, i. e. decreasing concentration of the raw material at its locations of extraction) may play a role, but over time new reserves can be developed by improved prospecting and extraction methods. However, even when considering mineral resources with this aspect as quasi-infinite with respect to their geochemical abundance, the extraction of a certain material with more sophisticated techniques from reserves with progressively lower ore grades is more energy demanding. A situation of “effective exhaustion” of a reserve might occur, when the costs (such as for energy, water, or environmental impact) for producing the raw material can no longer counterbalance the return [3].

At this point of the discussion, it is necessary to establish a clear distinction between the terms *reserves* and *resources*: By definition, *reserves* are those sources of a material that can be exploited with presently common technologies and under current economic aspects. Reserves are usually well identified and evaluated.
On the other hand, mineral deposits that can be potentially mined in the future are called *resources*. The reasons why resources become available for exploitation in the future can be manifold and of technological, economic or political nature, for example. Therefore, with the availability of new information, new techniques, changes in the market or with respect to legislation or policies, resources may be re-classified as reserves. It is also possible that reserves cease to be accessible for mining and therefore become resources (again). This classification of resources and reserves as part of resources is illustrated below in Figure 1.

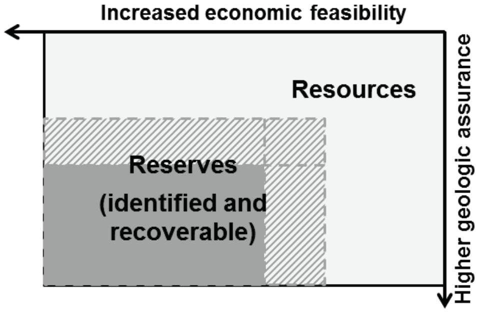

FIG. 1: Schematic diagram illustrating the classification of resources and reserves: *Resources* are deposits of sufficient concentrations so that economic extraction of a material is currently feasible or may become so in the future. With increasing degree of geological assurance of their existence (vertical scale) and increasing degree of economic (and technological) feasibility (horizontal scale), resources might be re-classified as *reserves*, i. e. the portion of resources that can be economically mined at the time of determination (adapted from [4]).

Apart from geochemical aspects, raw materials may become scarce in an economic sense, if the demand is equal to or higher than the amount of a metal or mineral available on the market. Consequently, it is economically "more difficult" to obtain this material, usually associated with higher prices. The reasons for a situation in which demand for a raw material exceeds supply, or decreasing supply is no longer satisfying demand, can be manifold; some are very specific to one material, or a group of metals or minerals.

Criticality studies trying to assess the short-, medium- or long-term availability of materials have to take into account all of the aspects discussed above. At the same time a compromise must be found between a realistic modelling of the processes involved on the one hand, and a necessary generalization and abstraction of the complex, dynamic and material-specific influences on the other hand. Several such studies and reports have dealt with the criticality of raw materials, considering national concerns [2] or technological impact [5], [6].
The goal of the present paper is to discuss the issue of critical materials and their potential future scarcity such as it may arise in the context of aviation. In particular, the continuous growth of air traffic expected for the next decades as well as the increasing push towards the use of new "green" technologies for future aircraft may have a significant impact on the materials' importance – and hence potential criticality - for aircraft design.

Today, approximately 20.000 aircraft are operated worldwide; their number is expected to increase to more than 40.000 by 2032 as passenger traffic is forecasted to grow around 5% annually [7], [8]. Due to this fast growth aviation's greenhouse gas emissions are likely to increase threefold by 2050, far exceeding their current contribution to global emissions of 2% [9]. With this probable development in mind, industrial as well as political actors have agreed on ambitious emission reduction targets: Firstly, the global aviation industry committed itself to a net carbon neutral growth from 2020 onwards and to a 50% net CO_2 emission reduction by 2050 compared to 2005 values [10]. Secondly, with the "Flightpath 2050" document the European Union targets to improve fuel efficiency on aircraft level to reduce CO_2 emissions by 75% until 2050 compared to an aircraft of the year 2000 [11]. Against the backdrop of these politically advocated development goals, aviation industry puts in great efforts to develop radical new technologies to make an important contribution towards these European and global environmental targets. One example is the continuously increasing research effort devoted to future concepts of "electric flying".

The impact of increased use of electrical energy, or of "green" forms of energy in general, on the supply of certain resources is a topic of ongoing discussion. Many different viewpoints are discussed in the literature. One reason for the controversy may be the genuine lack of reliable data. This especially concerns data or estimates for the current and future supply of some raw materials. Since in many industry sectors "electric" technologies are only beginning to enter the market to a noticeable amount, estimates of the raw material demand resulting from their increased future use are necessarily associated with uncertainties. This issue, however, is difficult to avoid since the transition to "greener" technologies e.g. in the transport sector cannot be expected to be completed in one decade, and any estimation about the resulting raw material requirements must therefore consider longer time periods.
Possible resource constraints from increased electrification have been investigated for electric vehicles [12], [13], [14], with varying results. The aim of the present study is to examine, which raw materials may be essential for electric propulsion of aircraft and whether a technology-driven supply risk could have major implications for the full electrification of aircraft.

A pre-concept study for an electrically powered mid-size aircraft forms the baseline of the present study. In particular, the electrical technologies assumed to be installed on this conceptual aircraft are used to determine the future demand for certain raw materials for fully electric air transport. These technologies and required principal materials are described briefly in the next section. Using some assumptions and previous work by one of the authors an estimate of the global fleet of universally electric aircraft in 2035 and in 2050 is presented after that. The assessment framework used for the identified raw materials and related metrics are then presented. This is followed by the application of the framework to several defined raw materials, namely lithium (Li), neodymium (Nd), dysprosium (Dy) and yttrium (Y). The conclusions in the final part of the paper sum up the results.

2. TECHNOLOGIES FOR UNIVERSALLY-ELECTRIC AIRCRAFT – THE CE-LINER EXAMPLE

Starting in 2011, Bauhaus Luftfahrt has conducted an in-house interdisciplinary design study dedicated to the integrated loop-zero assessment of a universally electric aircraft solution, the results of which were presented in [15]. The goal of this work was not only to identify the possible potentials (with respect to emission and noise savings etc.) of electric flight, but also to highlight and quantify the challenges with respect to key technologies and operational aspects of such a radical approach towards new aircraft propulsion methods. As the targeted year of Entry Into Service (EIS) the year 2035 was selected, meaning that the assumed technology status of the employed components should reflect improvements from the present state of the art up to the year 2030.
The resulting airplane, the so-called "Ce-Liner", is a tricycle, monoplane, low-winged twin-fan with podded mountings located on the aft fuselage. The standard configuration accommodates a maximum of 189 passengers (single-class). The Ce-Liner is powered via two "Silent Advanced Fans utilizing Electrical power" (SAFE) devices. Each rotating fan is driven by a High Temperature Superconducting (HTS, see Section 2.2) electric motor via two sequentially arranged planetary gearbox stages.

When it comes to operations and utilization, the efficiency of short-range aircraft like the Ce-Liner is driven by their ability to allow short on-ground times. Thus, optimizing turn-around time to 30 minutes has been one of the primary requirements for the design. Even at the advanced 2030 technology status assumed for the Ce-Liner, recharging a total energy content of around 60 MWh as required for the design mission (including provisions for reserves and contingencies) within this targeted turn-around time was considered prohibitive for the battery technology. A novel approach utilizing battery containers (the Charge-Carrying Containers, “3Cs”) housed in standardized LD3 containers was therefore developed. These 3Cs should enable a quick turn-around of the aircraft by simple replacement of used battery containers with charged ones by standardized ground-handling processes; additionally, this LD3 housing makes the energy-carrying batteries a modular component of the Ce-Liner, which can be easily substituted with advanced battery technology status even after the aircraft has entered into service.

For the design mission of 900 NM (1667 km), 14 batteries are required, which are located in the lower deck compartment (see Figure 2 below). The wide body, twin-aisle circular cross section offers sufficient volume for baggage and batteries.

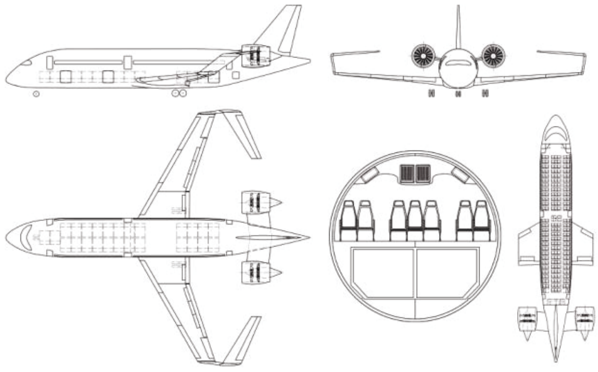

FIG. 2: Three-view and cabin layout of the pre-concept study „Ce-Liner“, designed as a universally electric aircraft.

The Universally-Electric Systems Architecture (UESA) of the Ce-Liner is divided into three different main systems, all representing different power and voltage levels. The first level, dedicated to the propulsion system, is characterized by high power and voltage. The second level caters to on-board consumer system requirements such as i) non-essential, e.g. galleys; ii) essential, e.g. flight control; and, iii) vital, e.g. emergency lights. This is associated with a medium power and voltage. The third level, with relatively low power and voltage demand, feeds the avionics equipment [16].

2.1. Energy Storage

The electric energy consumed by the Ce-Liner is stored in advanced lithium batteries with an assumed gravimetric energy density of 2.0 kWh/kg at cell level at the Ce-Liner’s EIS [15]. Today, numerous different battery system options exist, in which various specific cell electrochemistry configurations are realized; each of these exhibit certain advantages and disadvantages [6]. For example, a very high energy density can be obtained using a cobalt-containing cathode; however, the above-cited level of battery technology reaching the energy density values targeted for commercial electric aircraft like the Ce-Liner is yet to be reached. The gravimetric energy density value adopted in the Ce-Liner study should therefore be considered as a benchmark and development goal, for which an economically attractive electric air transport task is possible.

With the detailed development of the advanced lithium batteries still to be undertaken, the amount of Li contained in these future batteries is difficult to quantify. Nevertheless, for a first order approximation, the lithium-cobalt electrochemical combination used in today’s batteries shall be used here in order to estimate the overall Li-content of a battery. According to [6], it is approximately 180 g Li per kWh. This value is somewhat higher than those stated by other sources, see e. g. [18], but it is of the same order of magnitude. Other materials needed for manufacturing current batteries, e. g. cobalt, are not covered by the present study, reflecting the fact that the precise cell chemistry of the Ce-Liner’s advanced Li-batteries is not known.

With this approach it is possible to estimate the total Li-content in one Ce-Liner aircraft if one accounts for the number of LD3 battery containers and the total amount of energy in kWh stored for a typical mission. However, providing batteries only for aircraft in operation is not sufficient. Instead, in order to ensure a short turn-around time for each aircraft after landing, a certain number of batteries must additionally be held in stock at the airport for servicing aircraft on ground and replacing empty energy storage units with charged ones. In contrast to other potentially critical electrical materials discussed below, Li is therefore not only necessary for the batteries in use aboard the aircraft, but for all batteries in circulation, resulting in a larger number.

A first estimation of global battery demand for electric-powered transport aircraft [19] like the Ce-Liner concept can be developed starting from the analysis of the corresponding battery demand for Germany carried out in [20]. These results are then combined with 2012 Official Airline Guide (OAG) worldwide traffic data and mean growth rates from eleven different aviation traffic forecasts [21], which are needed to extrapolate the 2012 traffic data to the year of interest 2030. Without relying on any more detailed forecast for 2030+, it was assumed that aviation growth rates continue as before. Furthermore, it was assumed that aircraft *type* operation between two airports, i.e. short- to medium-haul aircraft or regional aircraft, does not change with respect to the 2012 status reflected in the OAG data.

In order to “translate” this current aircraft use into numbers for the Ce-Liner electric reference aircraft, a determination of replacement potential of current short-to-medium haul aircraft with the Ce-Liner concept was carried out. It is then straightforward to establish the resulting battery demand at 12 different German airports as a function of their recharging time, again using 2012 traffic data. Correlation plots between flight movements, recharging time and battery demand were combined with flight movements in the years 2030, 2035, 2040 and 2050 based on the above-cited traffic forecasts. Figure 3 shows the global battery demand for an assumed (highly ambitious) recharging time of 2h. Not included in these estimations are battery buffers in case of battery malfunctions or flight schedule disruptions. The presented numbers are therefore a first order estimate for the “battery inventory” that has to be provided to enable the worldwide operation of electric Ce-Liner-type aircraft under the given assumptions for air traffic and aircraft use. Replacement of batteries due to wear and damage, and hence performance degradation, is also not included.

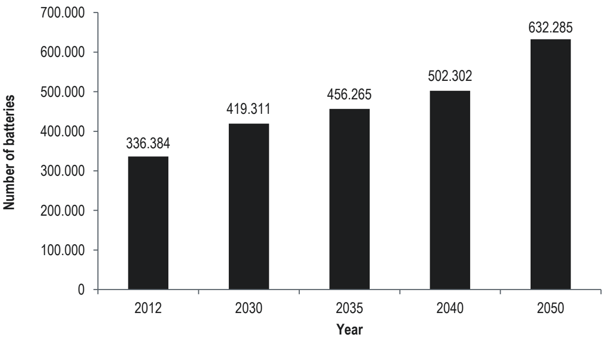

FIG. 3: Worldwide battery demand for 2012, 2030, 2035, 2040 and 2050 for Ce-Liner operations.

2.2. Power Transmission

Aboard conventional aircraft using kerosene as an energy carrier, the provision of the fuel to the turbo-engine is performed by a sophisticated fuel management and distribution system. For future aircraft with electric propulsion like the Ce-Liner, the equivalent task will be carried out by the Power Management And Distribution (PMAD) system. Necessary components in the PMAD are, for example, cables, switches, converters and connector elements. In particular, the power system architecture realized by the connections between switches, converters, power sources and power consumers reflects the previously mentioned three power (and voltage) level structure with for high (propulsion level), medium and low power requirements.

In terms of potentially critical materials, the biggest “footprint” is to be expected from cables required to transport electrical power from its source, e. g. the batteries, to the different consumers. In principle, these cables can be made of normal conducting materials such as copper (Cu) or aluminum (Al), or they can be superconducting[1]. While for the former it is essentially the required conductor strand diameters that determine the amount of metal needed (and its weight impact), the HTS materials, due to their exceedingly good conduction behavior, are employed inside superconducting cables only to a very small portion. The bigger material requirement results from the metal matrix (of Cu, or even silver) into which some HTS filaments have to be embedded, and possibly also from the required cooling infrastructure.

In the Ce-Liner concepts used as an electric baseline aircraft here, power transmission from the batteries to the electric motors is assumed to be performed by HTS cables. Since also the electric motors employ HTS technology, the main demand for these materials will be from their use in the motors, while the cables should result in only a small additional amount. Therefore, power transmission does not separately enter into our estimation for the required HTS material amount.

2.3. Power Conversion by Electric Motors

For an electrically powered aircraft, an electric motor converts the provided electric energy into mechanical energy by turning the shaft of the fan, resulting in propulsion. During the Ce-Liner study at Bauhaus Luftfahrt several electric motor designs, technologies and topologies were considered. Again, a principal distinction can be made between those motors relying on conventional conductor materials (like Cu and Al) and the superconducting materials.

Among various motor designs and topologies using conventional conducting materials, Permanent Magnet Synchronous Machines (PSM) appear to be the most promising for very high power density applications such as in traction or aircraft propulsion. To generate the electromagnetic field for power conversion inside the motor, powerful permanent magnets (PM) are used, usually containing neodymium-iron-boron (Nd-Fe-B, more precisely $Nd_2Fe_{14}B$). For operational reasons dysprosium (Dy) can be added for enhancing the magnets’ stability at high temperature. Neodymium and dysprosium are both lanthanides, commonly known as rare earth elements (REEs). Nd-Fe-B magnets are of importance to many modern technology sectors; they are not only used in large electric motors e. g. for electric vehicles and wind generators, and potentially for aircraft propulsion motors, but also in small electric motors, in positioning systems in hard-disks of personal computers, in tomographs and spectrometers [6].

Information concerning the amount of permanent magnet materials or more precisely of Nd and Dy, required for the construction of large electric motors, is difficult to obtain. However, some data can be found for wind power generators, but they vary a lot, covering a range from 40 kg to 300 kg Nd per MW and 4 kg to 35 kg Dy per MW of power performance [18], [22]. In general, a permanent magnet generator can also be operated as a motor; taking a conservative average of the numbers given above, a value of 150 kg Nd per MW and 19 kg Dy per MW of the PSM power performance is assumed.

Size and weight of the magnets eventually become prohibitive to motor designs for mobile high power applications. In order to increase the magnetic field beyond the capabilities of high performance PM, the use of superconducting materials is again an option: Superconducting windings can be used instead of Cu windings in the stator or the rotor of the electric motor. Even with the penalizing cooling requirements to maintain the superconducting properties of the windings in the working environment inside the motor, this results in a considerable reduction in the machine’s volume and weight (by 30% or even up to 50% [23], [24]). Also the efficiency of the motor can be improved, reaching up to 99% [16]. Currently, HTS motor designs are studied for applications in ship propulsion and large wind generators, where only for the rotor windings superconducting materials are employed, while the stator is conventionally conducting and equipped with Cu windings [25]. For future applications, however, the development of all-cryogenic machines seems possible, where both rotor and stator windings are made from superconductors [26], which should lead to further reductions of weight and volume of the motor, though a certain penalty for the size and power requirements of the cooling system must be expected. A detailed investigation on HTS electric propulsion systems

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[1] Superconducting materials lose their Ohmic resistance to direct current (DC) below a critical temperature T_c and consequently have much higher current-carrying capacities than normal metallic conductors. They need cryogenic cooling. For high temperature superconducting (HTS) materials T_c is above the boiling point of nitrogen, i.e. above 77K.

for aircraft including mass and efficiency estimations can be found in [16]. There the total amount for superconducting material in an all-cryogenic motor was quantified to be approximately 15 kg for an electric motor meeting the power demands of the Ce-Liner.

For the realization of such HTS electric motors, the use of a variety of HTS materials seems possible. During the Ce-Liner study, the HTS material YBCO ($YBa_2Cu_3O_7$) was selected. YBCO usually is deposited on flexible metal tapes coated with buffering metal oxides. For the present work, a 10 mm wide tape of nickel and copper was assumed, with an YBCO layer of 1,5 µm thickness. Y comprises 13,35 wt% of YBCO and therefore only contributes 0,07 wt% of the metallic tape, i. e. the superconductor. Consequently, for an all-cryogenic motor of the power rating assumed for the Ce-Liner approximately 10 g of Y are needed.

3. ASSESSMENT FRAMEWORK FOR RAW MATERIALS

In literature many criticality assessments for selected raw materials can be found; the number of reports addressing the availability of certain materials increased from below 40 in the 1980s and in the 1990s to nearly 200 published from 2000 to 2011 [27]. However, there is no consistency in the methodology, the criteria on which a material's criticality is assessed differ from one study to another, also depending on the aim of the study [1]. Usually a list of factors that (might) have an influence on the future availability of a material is compiled. A selection of raw materials is then scored and weighted against these factors.

In the study discussed in the present paper, metrics for
a) a risk of insufficient supply and
b) the importance of the technology for aviation
were set up. Factors for insufficient supply were in their majority based on other publications in order to provide some uniformity. To our knowledge a criticality study specifically tailored for aviation industry does not exist, therefore a new set of factors was defined for reflecting the importance of a certain raw material in aviation.

Some of the factors are quantitative and calculated in concrete numbers from the assumptions presented above, while other factors are of qualitative nature. In both cases a score from 1 to 5 is assigned to the factors, which are weighted according to their expected influence on availability. The sum of the weighted scores for the supply risk and the importance for aviation industry, respectively, are then normalized and represented graphically in a two-dimensional "criticality map".

3.1. Metrics

The chosen metrics for the criticality evaluation of raw materials are listed and shortly described in the following.

Supply risk:

- Factor of future demand
  In the context of criticality of raw materials, the years remaining until resources are depleted are sometimes used as a measure for geological availability. However, this estimation is based on static reserves and static annual consumption, but in reality both parameters are highly dynamic. On this account another parameter, referred to as the "Factor of Future Demand" (FFD), is used in the present work. It is defined as the projected demand for a given point in the future in relation to the reported production in a defined year of reference, at which the production is known with a certain degree of accuracy. Here, 2011 was selected as the base year offering a trade-off of up-to-date and complete data.
  The FFD as the ratio between the estimated future demand in 2035 and 2050, respectively, and the global production of the material in the defined base year 2011 is used in order to classify the geological availability of a raw material in terms of supply risk. An FFD of 1 means that the produced amount of a metal or other raw material in 2011 is needed to meet the future demand for the considered number of technologies.

- Concentration of the raw material in few countries
  If mining and production of a material is taking place only in few countries, production is more likely to be disturbed at an outage of one producer. Therefore, the material has to be rated as more critical as if the production is distributed over a greater number of countries.
  The concentration of a raw material in only few countries is reflected by the Herfindahl-Hirschenfeld-Index (HHI). The HHI is based on the market share of a country in production (see for example [28] for further reading).

- Geopolitical-economic availability of the raw material involving political, regulatory and social factors
  Supply is more susceptible to disruption if not only the production is concentrated in few countries but also if these countries are political unstable or if national policies restrict the availability. In the present work the HHI, used to determine the concentration of production, is therefore weighted by the World Governance Index (WGI) [28] that consists of six indicators. These are voice and accountability, political stability and absence of terrorism, government effectiveness, regulatory quality, rule of law and control of corruption. The "total" WGI for one country is determined by generating the mean value of these six factors.

- Recycling rate (secondary production)
  Recovery of raw materials either in the pre-consumer phase, e. g. during mining or from scrap from manufacturing processes, or in the post-consumer stage from end-of-life products is essential to cover increased supply. Estimating future recycling rates is extremely difficult as not only technological feasibility plays a major role but also economic parameters. For example, in some countries lithium batteries are already recycled today, but not for their Li content but for cobalt and nickel, which have currently a higher market value [29].

- Raw material extracted as a by-product
  Some minerals are mined because of a principal raw material, providing supply of other raw materials that are present in the mineral as well. The production of zinc within the extraction of copper is one well known example. However, the production of the minor raw material is then intrinsically tied to the production of the major material; if the latter ceases, production of the by-product is disturbed.

- Substitution potential of the raw material
  Materials may be substituted by alternative materials that are less critical. Restricted availability can push developments in this direction, although a decline in performance often goes hand in hand with the

substitution.

Environmental factors are considered important as well; however, they are not included separately in the metric for availability because a higher environmental concern can be reflected by higher production cost, resulting in a higher price depending on environmental restrictions, which are usually very specific to regional/local policies, regulations and single raw materials. The scope of the present work though is to provide a general assessment framework.

Importance for aviation industry

- Number of competing technologies/industries
  Competition for raw materials usually increases prices and raises efforts to get hold of the material, e. g. strategic alliances are forged. In a highly competitive market it is more likely that a certain material is drawn off by another industry than aviation.
- Market share of the technology in aviation (in comparison to other industries)
  Aviation is more vulnerable to the disruption of the production of a certain technology if the market share for the application in aviation is high. For future technologies this factor can only be roughly estimated.
- "Weighted weight" of the raw material in the aircraft
  This parameter was defined in order to represent the "material intensity" of the product, i. e. the aircraft. It is composed of two factors: the share (by weight) of the raw material due to the implemented technology onboard and an estimated substitution potential of the technology. This factor indicates a (qualitative) probability for the realization of the aircraft, even when a certain raw material and hence a technology is unavailable.

4. EVALUATION OF ESSENTIAL RAW MATERIALS

4.1. Lithium

As described above, energy for the exemplary aircraft is supplied by high performance lithium-ion batteries. The exact technology is yet to come in order to meet the ambitious Ce-Liner requirements. However, as Li is a lightweight alkali metal with an extremely negative electrochemical potential, it is supposed that, even after further research and development, batteries containing Li still would be the electric energy supply of choice.

Lithium, in the form of Li carbonate, Li hydroxide or Li chloride is produced mainly from hard rock and from brines of salt lakes, but recovery from sea water is under research as well (see for example [30]).
In batteries Li carbonate, Li hydroxide and Li metal (produced by electrolysis) are applied. Apart from the use in batteries, Li finds application in the ceramics and glass industry, in aluminum production, for lubricant greases and various other applications like catalysts and absorbers, but the fastest growing market is its employment in batteries [29]. In 2011 most of the produced Li batteries were used in electronic devices like portable personal computers and tablet computers and mobile phones; batteries for automobiles required 5% of the global production [29]. Although today a small market, it is assumed that the rapid growth of electric vehicles will consume a large part of the produced lithium [18], [31].

Currently, prices of Li (1-2% of battery costs [12]) do not emphasize research for reducing the Li-content in batteries. Furthermore, substitution of Li-based cell chemistries is difficult, although other material systems are under research [18]. These alternatives, however, are far from mature and are not expected to replace Li-based systems in the medium term.
Recycling of end-of-life batteries on the other hand might become an important source of Li in the future when high recycling rates may be realized [18]. In 2011 only 3% of Li was recycled and reused within the battery manufacturing industry [29]. A first legislative step towards increased battery recycling was the Directive 2006/66/EC of the European Parliament and of the Council [32], which regulates minimum collection rates of spent batteries for member states of the European Union and stipulates recycling. However, for reaching a recycling rate of Li that meets half of future supply [33], more targeted legislation and economic incentives are necessary.

4.2. Yttrium, Neodymium and Dysprosium

Yttrium, neodymium and dysprosium are REEs, which comprise the lanthanide group of elements with atomic numbers 57 to 71. REEs are not especially rare, but their geochemical concentrations are usually low and they are difficult to extract and separate. Although Yttrium (Y) is not a lanthanide element, it normally is ranked among these because of its chemical similarity and its natural occurrence together with lanthanides. All REEs have in common that they are not mined in their elemental form but as oxides. The global demand for REEs has increased significantly in line with their expansion into different emerging high-end technologies over the past two decades; they are becoming increasingly important in today's society because of their use due to environmental and economic reasons. In 2011, 94% of the world production of REEs came from China, but this is expected to decrease to 70% by 2015 [34].
Each REE has very unique properties that are exploited in high-technology applications. A consequence is that substitutions of specific REEs in a certain technology are not feasible; it is more supposable that completely different technologies are used instead, e. g. other permanent magnet systems.

Main uses for neodymium and dysprosium are permanent magnets for various applications, ranging from medical equipment and loud speakers to electric motors for automobiles and wind power generators [18], [22]. The extensive use of these REEs might be reduced by up to 30% by improving manufacturing techniques [18]. Additionally, material intensity may be reduced by changing to other motor systems, e. g. induction motors or hybrid PM motors, or by using other magnets, samarium cobalt or iron nitride, for example [18]. Another viable alternative is the employment of HTS materials instead of permanent magnets (see Section 2.3). This suggestion is addressed in the materials' assessment by evaluating the use of yttrium as an element used for superconductors. Y is used today mainly for low energy lighting, in microwave generators and lasers, for chemical applications, e. g. catalysts, and in metallurgy [35].

Data for the production of REEs, notably individual REEs, are not easily accessible. For the present study data from [36] were used, combined with information from [37] in order to estimate the world production of neodymium and dysprosium in 2011. For yttrium the U.S. Geological Survey (USGS) published data in [35]. Y is present in most REE deposits, resources are estimated to be very large [35].

Unfortunately, also the information about estimated reserves are inconsistent [18]: While the USGS places China as the principal reserve-holding country, holding approximately 50%, the Chinese Society of Rare Earths states that Brazil and China would have the majority of global reserves. The German Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) ranks China and the Russian Federation among the potential main producers of REEs [38].

Recycling of REEs is still in its early stages. Many uses of REEs are dissipative, and low concentrations are impeding effective recycling. A small amount of permanent magnet scrap is currently recovered in pre-consumer recycling [33]. However, potentials of REE recycling are assumed to be significant [18].

4.3. Criticality Maps

Data for production rates, primarily from the USGS, technological estimations and the information given above were used to analyze the raw materials that have been identified as essential to the full electrification of aircraft, namely Li, Nd, Dy and Y in the case of the Ce-Liner. Projections of supply and demand are made for the aircraft's year of EIS 2035 and for 2050. In 2035, a marginal market share of 5% of all operating short-haul aircraft is supposed. For 2050, however, it is assumed that 80% of the global fleet of mid-range aircraft are of the Ce-Liner-type, corresponding to 100% market penetration as not every mid-range route can be operated by the Ce-Liner (see [20] for details).

The normalized values for factors indicating the impact of supply disruption on aviation and for factors that are reflecting a certain supply uncertainty are graphically represented in two-dimensional "criticality maps" for both 2035 and 2050, shown in Figures 4 and 5, respectively.

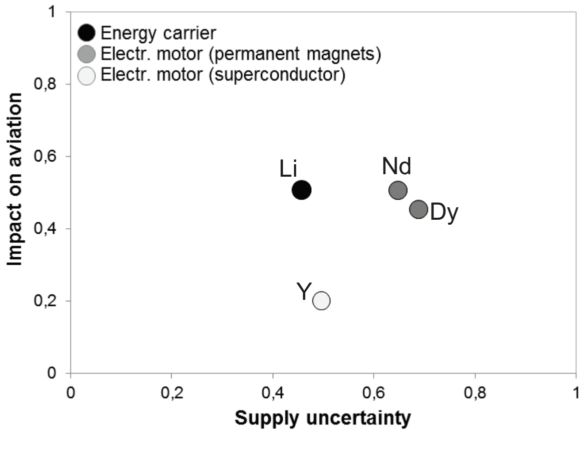

FIG.4: Criticality map for Li, Nd, Dy and Y for the year 2035.

In 2035, the supply of the REEs Nd and Dy has the highest uncertainty, mainly due to the expected increasing demand in various different technologies of the "green energy" sector. However, for aviation their importance is medium, as it is for Li, because the share of universally electric aircraft is assumed to be small in 2035.

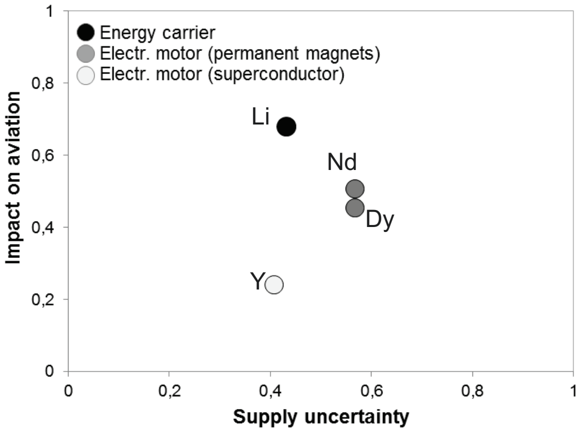

FIG. 5: Criticality map for Li, Nd, Dy and Y for the year 2050.

The demand of aviation especially for Li increases significantly with estimated projections for 2050; a great number of batteries must be present for operating a large fleet of electrically powered aircraft. The supply uncertainty for Nd and Dy decreases marginally, however, their importance for aviation decreases as well, because alternative technologies dispensing with permanent magnets are expected to rise.

For Y the uncertainty in supply relieves slightly, basically due to an assumed growth in the number of sources, including (improved) recycling. The employment of superconducting material might facilitate full electrification of aircraft and additionally make aviation independent from permanent magnet materials like Nd and Dy. Y might therefore become a key material for electric flying. At the same time the amount necessary for one aircraft is very small (approximately 10 g) and Y-containing superconductors are only one possible choice of several superconducting materials; consequently the material's impact on aviation is rather small.

In Table 1 results for the estimated demand of raw materials in a fleet of Ce-Liners in 2035 and in 2050 is compared to the FFD defined earlier as the ratio of the projected demand and the global production in the base year 2011.

			Lithium	Neodymium	Dysprosium	Yttrium
Global demand Ce-Liner	2035	[t]	15.440	5.867	880	0,057
	2050	[t]	427.930	129.424	19.414	0,314
share of global prod. in 2011	2035		0,44	0,36	3,46	0,000006
	2050		12,23	7,88	76,43	0,000035

TABLE 1: Demand of Li, Nd, Dy and Y based on the application in the Ce-Liner (in total numbers and in share of the worldwide production in 2011) for 2035 (5% of all mid-range aircraft worldwide are fully electric) and for 2050 (80% of all mid-range aircraft worldwide are fully electric).

In order to meet the demand solely for aviation industry in 2035, approximately half of the total 2011 production of Li is used. The situation for similar for Nd; Dy-production should be 3 times higher than in 2011. Only for Y the FFD indicates no necessary raise in production.

For the year 2050, with a much larger number of Ce-Liner-type aircraft operating, the situation especially for Li aggravates, although also for Nd and Dy the demand is expected to exceed the 2011 production level many times. It must be mentioned, however, that the FFD does not express potential supply limitations but only indicates by how many times a historical production level (in this case that of the year 2011) has to be scaled up to meet future demand.

5. CONCLUSIONS

The present study has investigated the future supply situation of some raw materials required for fully electric aircraft, with a focus on lithium for advanced energy storage, neodymium and dysprosium for permanent magnets in highly efficient electric motors, and yttrium as a constituent for superconducting electric components. Important parameters entering into the assessment of future demand and supply in aviation were identified; these include historical supply (based on data for the base year 2011) and substitution potential for the supply side; on the demand side the future market size, the market share of the relevant technology taken up by aviation, and the material intensity were considered.

Estimations for the material demand were made for the years 2035 and 2050. Evidently, projections for such long periods into the future increase the level of uncertainty, especially since the available forecasts for material supplies do not reach this timeline. Additionally, there is only limited data on the material intensity of many technologies of interest, i.e. information about the amount of material necessary for the investigated technologies, and the available numbers usually exhibit a wide uncertainty range. In the present work average values for the material intensities were used in order to assure conservative estimates.

Aside from the two uncertainties cited above, there is also no information about the future market share of commercial electric air transport, given the radicalness of this new propulsion approach and its current fundamental research status. The results of our study are based on the (rather aggressive) assumption that in 2050 *all* aircraft movements that *can* potentially be operated by an aircraft of the Ce-Liner-type actually *are* carried out by universally electric medium-haul aircraft. In this way the upper limit of the considered materials' demand is studied, or, as one may say with respect to their (potentially limited) availability, a “worst case scenario”.

Any future assessment of the availability of raw materials for aviation should therefore work towards the reduction of these uncertainty levels. Moreover, further work on the assessment methodology itself should include refinement of the presented assessment framework. Different scenarios for future markets might help to narrow down the uncertainty range. Also, the number of quantitative factors in the framework should be increased at the expense of the qualitative ones; however, one of the biggest challenges is to get relevant and reliable data, especially on production levels and the material intensities of the technologies of interest.

In the case at hand here, it was found that the demand for Li caused by electric aircraft in 2050 will be significant, exceeding the worldwide 2011 production by over 1200% - only for the demand in aviation. The situation is similar for Nd and especially Dy: Almost 800% of Nd and 7600% of Dy of the produced amount in the base year 2011 would be necessary for electric motors in commercial aircraft in 2050.

These numbers seem very high. However, for both lithium and REEs, the global resources are estimated to be substantial [36], [29], [18]. Therefore, with the ongoing development of production and extraction techniques, the improvement of recuperation and recycling technologies and the exploration of new reserves, even such high demands could possibly be met in 2050.

It has to be added that, in order to meet the increased future demand of raw materials that are essential for electric mobility, it is crucial to install legal frameworks and policies for recycling. Although primary supply from mineral deposits and other non-renewable sources is likely to increase with increasing economic importance and investments into new prospecting and extracting techniques, the re-use of materials and their re-entry into the supply chain (the secondary supply) must also contribute. For example, Mohr et al. [31] point out that increasing Li supply from 2030 onwards has to be met by recycling. Konietzko et al. [39] mention that, according to an assumed market penetration of 90% for electric (ground) vehicles in 2050, up to 30% of the currently known global Li reserves could be bound in batteries.

In addition to improved utilization of different material sources, the investigated technologies will advance over time as well. While for batteries the use of Li is likely to remain important in the future due to its extraordinary electrochemical and physical properties, the demand of Nd and Dy may be reduced or even eliminated by the development of other drive train concepts. One alternative considered here is the use of superconducting materials in electric motors, containing, for example, yttrium. The future availability of Y can be considered as good; the production level of 2011 would be largely sufficient for the assumed number of operating electric aircraft in 2050 (0,0035% of 2011 production is necessary). This is mainly because of the small material intensity in superconducting windings. Despite of the limitations that are inherent to long-term future projections of technology development and the resulting material demand and supply, we come to the conclusion that, from the point of view of required raw materials, there are no reasons, why the development of full electrification of aircraft should cease.

ACKNOWLEDGMENTS

The authors wish to thank P. Vratny and K. Petermaier for fruitful discussions and valuable comments.

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