Assessing Metal Use and Scarcity Impacts of Vehicle Gliders

Citation for the original published paper (version of record):
Bitencourt de Oliveira, F., Nordelöf, A., Bernander, M. et al (2024). Assessing Metal Use and Scarcity Impacts of Vehicle Gliders. Circular Economy and Sustainability, 4(3): 1851-1875.
http://dx.doi.org/10.1007/s43615-024-00353-x

Circular Economy and Sustainability
https://doi.org/10.1007/s43615-024-00353-x

ORIGINAL PAPER

Assessing Metal Use and Scarcity Impacts of Vehicle Gliders

Felipe Bitencourt de Oliveira[1,2] · **Anders Nordelöf**[1,3] · **Maria Bernander**[2] · **Björn A. Sandén**[1]

Received: 2 June 2023 / Accepted: 9 February 2024

Abstract

This study assesses the metal composition of two vehicle gliders, configured with different equipment levels and evaluates the risk of short and long-term metal scarcity. Entropy analysis is also used for insights on secondary metal recovery strategies. Fifty-five metals are evaluated, with gold, copper, bismuth, lead, molybdenum, and certain rare-earth metals (REMs) subject to the largest supply risks. Differences in equipment levels significantly impact the short-term supply risk for specific metals. Entertainment and communications equipment contain significant amounts of REMs, whereas mirrors and electrical infrastructure contain considerable shares of gold, silver and copper. Some metals are concentrated in a few components while some are dispersed across thousands, impacting recycling opportunities. The broad metal demand of the gliders underscores the automotive industry's role in supply risks for its own manufacturing needs and other societal domains. This emphasizes the significance of comprehensively evaluating metal requirements beyond powertrains for informed resource management.

Keywords Vehicle Gliders · Equipment Levels · Metal Scarcity · Metal Availability · Automotive Industry · End-of-life Vehicles (ELVs)

Introduction

The automotive industry is one of the major consumers of natural resources worldwide [1, 2]. Besides "industrially mature" base metals, such as iron, aluminium and copper, vehicles contain a wide variety of scarce, rare and minor metals.[1] These are present in a multitude of components, contributing to passenger safety and an improved driving experience. The

---

[1] Minor metals are metals typically found in ores alongside base metals and often incorporated into base metal concentrates and smelter feeds.

✉ Felipe Bitencourt de Oliveira
felipe.oliveira@volvocars.com

1 Division of Environmental Systems Analysis, Chalmers University of Technology, Vera Sandbergs Allé 8, 412 96 Gothenburg, Sweden

2 Volvo Car Corporation, 405 31 Gothenburg, Sweden

3 Institute of Transport Economics, Gaustadall´Een 21, 0349 Oslo, Norway

broad range of metals present in vehicles, combined with the large number of units being manufactured, leads to substantial stress on the global demand for metals [3–5].

Besides environmental and social concerns [6, 7], various metals found in modern cars have been identified as strategic or even critical to the automotive industry. This means they are associated with a high likelihood of supply disruption, with a limited number of viable alternatives [1, 8]. Consequently, the sector's growing attention to identifying metals of concern comes as no surprise [4, 5, 9]. From an automotive manufacturer's perspective, it is strategically relevant to have a clear picture of the metals present in cars, their quantities and in which parts and/or components they are present.

In recent years, stricter safety and environmental regulations, along with the push for comfort, digital connectivity, and automation, have led to a significant growth of the portfolio of metals used by the automotive industry [10–13]. For instance, as part of lightweighting strategies, aluminium alloys are replacing iron in engine blocks, wheels and various body-in-white[2] components [10, 14]. Minor metals such as niobium, molybdenum and vanadium are present as alloying elements in different types of advanced, high-strength steels [15]. The ongoing shift to electric powertrains has increased the automotive demand for lithium, cobalt, nickel and different rare earth elements [16, 17]. Likewise, metals such as palladium, tantalum, silver and gold are present in a variety of electrical and electronic equipment (EEE) that are integral to modern vehicles' operations [13, 18–20].

A growing body of literature has sought to identify and quantify the metals present in passenger vehicles, assessing their strategic importance to the automotive industry. Several early studies focused on automotive recycling, highlighting the broad use of major base metals like steel, aluminium and copper [21–23]. Recently, attention has shifted to minor metals (e.g., platinum group metals, rare-earth metals, lithium, cobalt) given potential supply risks [24–27]. Others have taken a more comprehensive view, mapping a broader range of metals across different drivetrain types, comparing the metal compositions of internal combustion engine vehicles (ICEVs) to electrified counterparts like hybrid electric vehicles (HEVs), plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs) [28–30]. In terms of methodology, studies have quantified metal content by analysing dismantled parts [18, 31], shredder output [31], or manufacturers' databases [1, 29, 30]. To assess metals strategically, studies have employed techniques like criticality analysis [30, 32, 33], resource efficiency assessment [34], and exergy analysis [28, 29].

These studies indicate that the growth of electric powertrains has notably increased the demand for certain metals, a trend predominantly driven by the material requirements for traction batteries and electric motors [2, 25, 28–30]. Yet, parallel to this electric transition, other trends also contribute to a rising demand of metals, impacting systems beyond the powertrain. These trends encompass lightweighting strategies and the increasing integration of electronic equipment in vehicles. Their significance and impact on metal demand threatens being understated due to the predominant focus on electrification.

To address this gap, this study takes a narrower focus, assessing the vehicle "glider" – all the subsystems of the vehicle except the propulsion system. The novelty of our methodology lies in its unique examination of non-powertrain components. By intentionally omitting extensively researched vehicle parts, we aim to highlight the demand for automotive metals that may otherwise remain unnoticed.

---

[2] The term "body in white" refers to the unpainted, pre-interior assembly stage of a vehicle, comprising its structural framework and outer panels.

The identified metals are analysed based on their global resource availability, a key parameter in scarcity assessments. Resource scarcity represents a situation where demand for a resource surpasses its supply [35]. In the short term, scarcity may arise from technical, economic, or other barriers to resource extraction and distribution, particularly when coupled with a sudden spike in demand. Conversely, long-term scarcity takes into consideration the physical limits of non-renewable resources, as continued use leads to extraction from ores with ever lower grades, potentially passing geological thresholds effectively leading to exhaustion [35].

Building on this foundation, this study employs two scarcity metrics – short and long-term metal availability – to investigate the implications of automotive metal demand. Specifically, we centre our attention on annual metal production, indicative of short-term availability, and the average metal concentration within Earth's crust, which provides insights into long-term availability. These metrics encompass the physical availability of metals. This study does not explore other factors of importance for metal scarcity, such as demand from other sectors, geopolitics and vulnerabilities related to the spatial distribution of supply and demand [35, 36].

To reduce reliance on scarce primary metal resources, it becomes essential to explore viable strategies. These include substitution with more abundant materials or managing metal life cycles more efficiently. Consequently, a secondary objective of this study involves an investigation into the distribution of metals across the various subsystems and components of the vehicle glider. To aid this analysis, we employ a measure of dispersion that provides insights into feasibility of substitution and different secondary metal recovery strategies. For instance, a widespread distribution of metals might complicate targeted recovery or substitution efforts, whereas a more concentrated distribution would likely simplify it. Beyond its significance for automotive manufacturers, these insights hold substantial value for key stakeholders such as automotive recyclers. They can aid in enhancing the efficacy of secondary recovery strategies for scarce metals, promoting a more circular materials management approach. Additionally, these findings can inform automotive design practices, encouraging the prioritization of more abundant metals in the transportation sector.

This work was conducted as a university-industry collaboration between Chalmers University of Technology and Volvo Car Corporation (hereinafter Volvo Cars). While Volvo Cars is the immediate recipient of the results, the authors believe that most of their findings will apply to the automotive industry in general.

Methods

In this section, we describe our approach to identifying relevant metals[3] in two vehicle gliders and their subsystems from the perspective of resource availability. To achieve this, we employ two distinct indicators to gauge short and long-term primary metal scarcity. While long-term scarcity is assessed by applying the crustal scarcity indicator [37], an indicator of short-term scarcity is developed specifically for this study, based on Andersson

---

[3] Throughout this work, the term "metals" also includes metalloids. This is to avoid excessive repetition and for conciseness.

[38]. Furthermore, we also describe how the concept of entropy is used to analyse the distribution of metals in the gliders.

Material Composition Data for Gliders

An assessment of the metals embedded in two vehicle gliders is performed. These gliders are based on the same car model from 2021, a petrol-powered compact sport utility vehicle (SUV) sold on the European market. The two gliders differ in terms of equipment levels; one is an extra-equipped glider (EEG) with the highest available equipment, while the other is a standard-equipped glider (SEG), with basic-level equipment. As for their representativeness, the gliders fall within the mid-size vehicle segment (C-segment). In 2021, the combined SUV sales across all weight classes (and all vehicles in the C-segment) accounted for 60% of all new cars sold in the European Union [39]. Further information about both the glider options can be found under Supporting Information, Table S1.

The material composition data for the assessed vehicle gliders is retrieved from the International Material Data System (IMDS). This industry wide database, jointly developed by automotive manufacturers, aims at facilitating vehicle manufacturers to collect, record and track material utilization, since it contains data on components and material content present in finished vehicles [40].

As previously described in Bitencourt de Oliveira, et al. [41], extracting material composition data from IMDS involves a sequence of steps. To produce a list of components for each glider, both are initially configured in Volvo Cars' Vehicle Construction Database. This is an internal database containing information on all individual components present in each vehicle manufactured at Volvo Cars. The components are arranged hierarchically according to different functional groups. Next, an algorithm developed by Volvo Cars matches all component identification numbers to their equivalent material datasheet stored in IMDS and generates the component material data list. This is a list of components which includes information on the material composition of each item. In this case, two lists were created, one for each glider.

Once the component material data lists are created, metals present in the gliders are identified by analysing their material constituent entries in the lists, referred to as *basic substances*. Basic substances may be chemical elements (such as iron or aluminium), standard compounds (such as acrylic resin or titanium oxide) or, in cases where confidentiality is required, a "wildcard" (e.g., "miscellaneous, not to be declared") [42].

Metals are found in a variety of forms in vehicles: as pure metals, as alloys and in various organic and inorganic compounds. Since the assessment is done at the elemental level, all metal content which was not reported at that level (but as compounds) is calculated using molecular formulas and the respective molecular weights of elements. This means that if a compound contains a metal in its molecular structure, we compute the proportion of that metal in the compound to determine its absolute content.

Whenever possible, the molecular formulas of the compounds are identified by the CAS (Chemical Abstracts Service) number assigned to the basic substance by IMDS. In cases where compounds were not registered with a CAS number (approximately 3% of the gliders' mass), best judgment was used to determine molecular formulas based on the textual descriptions of the basic substances. For instance, a substance described as "sodium soap for lubricants" (no CAS number) was approximated to "sodium stearate", a soap derived from stearic acid and frequently used as thickening agent in greases.[4] In a few cases ($<1\%$ of the gliders' mass), the textual description was a "wildcard" and, hence, no molecular formula could be applied. In these cases, no assumptions could be made, and the material was omitted (a limitation of the methodology).

Short-term Potential Primary Metal Scarcity Indicator

This newly formulated indicator based on Andersson [38], aims to identify relevant metals in the gliders by using a primary production supply risk perspective. The indicator is defined as the ratio between the metal demand of a hypothetical glider fleet and the global primary production of that same metal. The hypothetical glider fleet corresponds approximately to the annual worldwide production of passenger cars [43]. Consequently, the indicator shows how much of the global primary metal would be required if the EEG or SEG options were the only ones available on the market. The resulting metric is referred to as the "demand fraction of primary production" (DFP) for each metal. The DFP is designed to reflect the present or near-future state of the system under scrutiny; metals demanded by the automotive industry and their global supply. A high DFP indicates a potential risk of near-term shortage and that the automotive industry is contributing significantly to this shortage.

$$DFP_i = \frac{m_i \cdot F}{P_i} \tag{1}$$

where m_i is the mass of metal i (kg per glider), F represents a hypothetical annual glider production of 80 million units (gliders per year) and P_i is the annual global mining production of metal i (kg per year).

Annual production values for most metals in the gliders are drawn from the United States Geological Survey (USGS) [44] records for 2019. If no data for that year was available, the most recent published values are given. Although production output may vary from year to year, our aim is to obtain an order of magnitude that serves as an indication of the current production volume of a given metal. If production data is reported as the amount of metal ore extracted (such as chromite production for chromium), the total mass of metal extracted in its elemental form is derived from the molecular formula of the ore. Additionally, for metals whose annual production values are missing or not individually reported by the USGS (such as caesium and rare earth metals), other data sources are used. Sections C and D in Supporting Information have more information on the sources and production volumes used.

Long-term Potential Primary Metal Scarcity Indicator

The crustal scarcity indicator (CSI) method is used to assess the long-term availability of metals present in the gliders [37]. This mineral resource impact assessment method quantifies the decrease in resource stocks due to extraction and is characterised by a long-term global perspective on elemental scarcity. The method is based on the average crustal

---

[4] The molecular weight of sodium stearate is about 306.46 g/mol (assumed $C_{18}H_{35}NaO_2$), with sodium (Na) contributing 22.99 g/mol. This allows us to calculate that sodium constitutes approximately 7.5% of the total mass of sodium stearate, demonstrating how we determine the metal content in compounds.

concentration of elements in the Earth's crust. Due to its temporal reliability, methodological consistency and comprehensive coverage of elements [37], the method has advantages compared to other resource impact assessment methods, such as the abiotic depletion method [45] and surplus ore method [46].

The CSI is calculated as the product of the crustal scarcity potential (CSP) of a given metal and its mass. CSP values for the metals assessed in this study are extracted from Arvidsson et al. [37].

$$CSI_i = m_i \cdot CSP_i \tag{2}$$

Note that in Eq. (2), there is no need to evaluate the entire hypothetical glider fleet, as the purpose of the CSI is to compare the gliders' relative use of different metals to the long-term availability of those metals.

Furthermore, for the analysis in this study, different metals are grouped according to their overall contribution to the total CSI of the glider; in other words, their share of the glider's total CSI.[5]

$$\text{Share of glider's total CSI} = \frac{CSI_i}{CSI_{glider}} = \frac{m_i \cdot CSP_i}{\sum_i m_i \cdot CSP_i} \tag{3}$$

where m is mass in kg and i is a metal present in the glider.

Distribution of Metals in Subsystems

To assess the distribution of metals in greater detail, the gliders are divided into subsystems using an internal aggregation method used by Volvo Cars. This method groups components into larger assemblies that perform similar functions, resulting in a hierarchical structure of the vehicle and its constituent parts. This approach facilitates the identification of subsystems that are more vulnerable to supply risks and make a greater contribution to resource demand. In this study, a total of 21 subsystems were analysed. These included: advanced driver assistance, body structures, brake system, climate, doors and boot, driver controls, electrical infrastructure, exterior glass, exterior lighting, exterior trim, exterior visibility, instrument panel and console, interior trim and lighting, locking and security electronics, multimedia and communication, power supply, restraints, seating, steering, suspension, frames and mountings, plus wheels, tyres and accessories.

Distribution of Metals in Components

While the distribution of metals in subsystems provides a valuable overview of their presence within the glider, a more granular examination of the dispersion of metals across individual components can provide further insights. To this end, the distribution of metals at the component level is investigated using the concept of entropy. Entropy is both an indicator of the state of disorder in a system and a measurement of dispersion [47]. In the context of this study, entropy (dispersion) S of metal i is defined as:

---

[5] Note that the "total CSI of the glider" refers to the metal and metalloid content of the glider. Other elements, such as hydrogen, carbon and chlorine are not evaluated. Hence, in this context, the term "total CSI" represents the total CSI for our calculations only and not the absolute total CSI of the glider.

$$S_i = -\sum_j p_{i,j} \cdot \ln p_{i,j} \tag{4}$$

where $p_{i,j}$ represents the share of metal i present in component j:

$$p_{i,j} = \frac{m_{i,j}}{m_{i,glider}} \tag{5}$$

where $m_{i,j}$ is the mass of metal i (kg) in component j and $m_{i,glider}$ is the total mass of metal i (kg) in the glider.

A higher entropy value indicates that a metal is distributed evenly over many components throughout the glider, while a lower value indicates that it is more concentrated in specific components. This information can be useful in determining the effectiveness of different secondary metal recovery strategies, as a more even distribution of metals may render the extraction of specific metals more challenging. Conversely, a more concentrated distribution would likely make extraction easier and less costly. Substitution is presumably also a more viable option for scarce metals concentrated in a few components, as opposed to those evenly dispersed across thousands of components. It should be noted that the resulting indicator values depend on what is considered as "component". Despite this partly subjective aspect depending on conventions in the automotive industry, we believe the indicator provides useful information.

Results

Metal Composition of the Gliders

The analysis of the two glider options reveals the presence of 55 different metals in the EEG and 54 in the SEG, with the metal gadolinium (Gd) making up the difference. For one element, potassium (K), the concentration is lower in the EEG compared to the SEG. This is attributed to the reduced use of mica in the former. However, all other metals are present in larger amounts in the EEG, since more components are present in this glider. Figure 1 shows the mass variation of the metals found in the EEG in comparison to the SEG. For nearly half the metals (27), the mass variation is smaller than 10%. For the majority (48), it is less than 100%. For the remaining six metals present in both gliders, the mass variation is greater than 100%. Four elements (dysprosium (Dy), terbium (Tb), gallium (Ga) and germanium (Ge)) are found in much larger amounts in the EEG (> 1,000%). Indeed, dysprosium and terbium show the greatest mass variation between gliders; over 25,000% and 18,000%, respectively.

The mass of each metal found in the gliders varies greatly. Iron (Fe) and aluminium (Al) are by far the most common, jointly accounting for some 90% of the total metal mass in the glider. This is not surprising, as these metals are commonly used in many structural and mechanical components. The remaining 10% of the metal mass is distributed among 53 different metals in the EEG, with most of them present in small quantities. For instance, 35 of the 55 metals found in this glider weigh less than 100 g and 19 of them weigh less than 1 g.

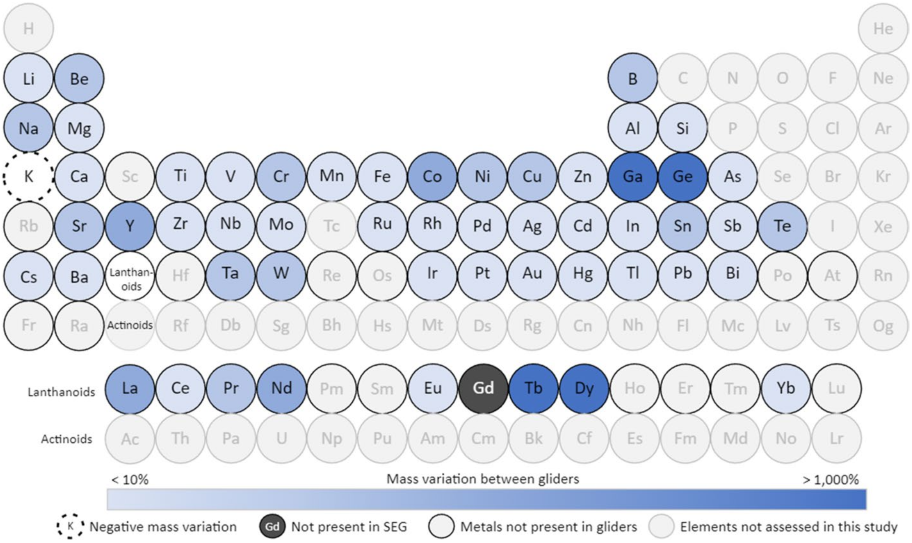

Fig. 1 Metals and metalloids present in the EEG and their mass variation compared to the SEG. Potassium (K) is found in lower amounts in the EEG, while gadolinium (Gd) is not present in the SEG

Assessment of Short and Long-term Potential Primary Metal Scarcity

From this section and up until the section "Distribution of Metals in Components", the results focus solely on the EEG, as this is the glider option with the highest level of equipment. Figure 2 shows our assessment of the short and long-term availability of the metals present in the EEG, with each dot representing a unique metal found in this glider. The y-axis defines the short-term potential scarcity of each metal (its DFP value), while the x-axis reports the long-term potential scarcity of each metal (its CSI value).

The metals assessed are divided into four groups, “Red”, “Orange”, “Yellow” and “Grey” to facilitate the visualisation of the most relevant metals in terms of short and long-term availability. The “Red” group clusters metals with a greater probability of supply risk associated with both short and long-term availability. Metals in this group have more than a 5% share of the total CSI of the EEG, while also demanding over 5% of their global production. This group includes gold (Au), lead (Pb), copper (Cu), bismuth (Bi) and molybdenum (Mo).

The “Orange” and “Yellow” groups also cluster metals having over 5% of their global production value. However, their shares of the glider’s total CSI differ; between 0.5% and 5% for metals in the “Orange” group and less than 0.5% in the “Yellow” group. When compared to the “Red” group, these metals have a potentially lower risk of supply constraints associated with their long-term geological availability. However, in many cases, there are similar supply risks regarding their short-term availability.

Finally, all the metals plotted in the “Grey” group have less than a 5% share of the glider’s total CSI and less than 5% of their global production value. This group gathers the metals with the lowest short-term supply risks, according to the indicator used in this study.

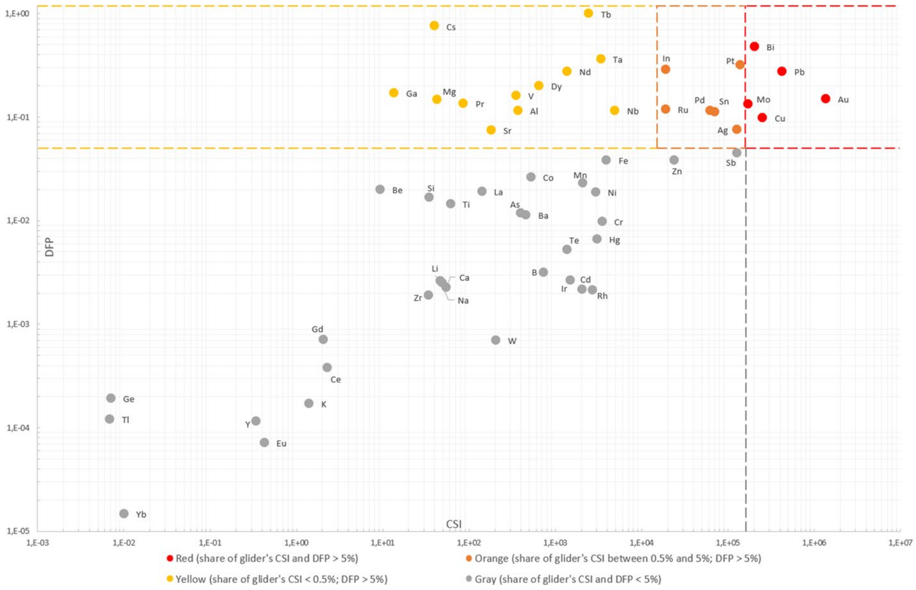

Fig. 2 Assessment of short and long-term potential primary metal scarcity for the metals found in the EEG. Short-term potential scarcity is defined by the y-axis, i.e., DFP (demand fraction of primary production) values, while the long-term potential scarcity is defined by the x-axis, i.e., CSI (crustal scarcity indicator) values

Gold accounts for almost half (~45%) of the glider's CSI, despite having a low mass content, amounting to only a few grams. In this study, this metal is at the greatest risk of long-term geological scarcity and is the only precious metal with a contribution exceeding 5% of the glider's CSI.[6] Gold is normally used as a coating for electronic components or for bonding wires in many semiconductor chips. Among the other precious metals analysed, platinum (Pt) in the "Orange" group has the highest DFP (~32%).

Lead and copper are two metals found in significant quantities in the EEG. Lead is used primarily in lead-acid batteries, while copper is present in various electrical and electronic components in vehicles. In terms of DFP, a hypothetical glider fleet would demand almost 28% of all global primary lead and 10% of all copper produced. Regarding their long-term potential scarcity, lead accounts for around 14% of the glider's CSI, with this value at about 8% for copper.

Bismuth and molybdenum are also in the "Red" group. Despite its low mass content, bismuth makes a significant contribution (almost 7%) to the CSI of the glider. This puts it at risk of long-term geological scarcity. Molybdenum has a similar CSI contribution (around 6%) but is present in larger quantities; in the EEG, its mass is nearly four times that of bismuth. In terms of short-term supply risks, bismuth has the third largest DFP of all metals (analysed at 48%), while molybdenum has a lower DFP (13%).

A total of ten different rare-earth metals (REMs) are found in the EEG. None of these are clustered in the "Red" group. Indeed, most REMs in the glider – cerium (Ce), europium (Eu), gadolinium (Gd), lanthanum (La), ytterbium (Yb) and yttrium (Y) – are clustered in

---

[6] Besides gold, the precious metals silver, platinum, palladium, rhodium, ruthenium and iridium are also present in the EEG.

the "Grey" group, indicating that they have a lower supply risk due to their potential short and long-term scarcity. However, there are four REMs in the "Yellow" group – terbium (Tb), neodymium (Nd), dysprosium (Dy) and praseodymium (Pr) – which show significant potential short-term supply risks. The hypothetical glider fleet would demand the entire annual global production of terbium and about a third of all neodymium produced.

Interestingly, caesium (Cs) has the second-largest DFP of all metals. Over 75% of the global production of this metal would be required by a fleet of 80 million EEGs. It is important to note that this evaluation carries a large degree of uncertainty since the statistics for the global production of caesium are based on estimates.

Distribution of Metals in Subsystems

As described earlier, the exposure to supply risks of the gliders' different subsystems is assessed. Table 1 shows the mass distribution of selected metals (those from the "Red", "Orange" and "Yellow" groups) within the EEG's different subsystems. The percentages are relative to the total mass content of each metal in the glider. Of the 23 metals evaluated, over half (12) are present in the "Multimedia and communication" subsystem in proportions greater than 10%. The REMs terbium (Tb), dysprosium (Dy), neodymium (Nd) and praseodymium (Pr) are all found in this subsystem in significantly higher mass shares ($>30\%$). These metals are primarily constituents of permanent magnets and are mostly found in the glider's sound system. The same explanation also applies to the metals gallium (Ga) and strontium (Sr).

As expected, large concentrations of palladium (Pd), tantalum (Ta) and ruthenium (Ru) are seen in "Multimedia and communication" and "Driver controls", due to the high number of electronic components in these subsystems. These metals are usually embedded in the capacitors and resistors of printed circuit boards (PCBs) that fulfil different functions.

The largest mass shares of copper (Cu) and tin (Sn) are found in the "Electrical infrastructure" subsystem. Copper is the main constituent of wire harnesses, while tin is widely used as solder throughout the glider. It is important to note that a significant share of tin is also found in the "Power supply" subsystem, since this metal is embedded in the glider's 12 V battery.[7]

Most silver (Ag), gold (Au) and indium (In) are present in the "Exterior visibility" subsystem, as these metals are used as coatings for external mirrors, to improve light reflection properties [48]. Additionally, a large mass share of silver is seen in "Exterior glass" (as it is part of the coating in heated windscreens) and in the "Electrical infrastructure" and "Multimedia and communication" subsystems, where it is mostly used as a constituent of lead-free solder (Ag/Sn alloy) in electric and electronic components. It is worth noting that "Multimedia and communication" also contains around 15% of all gold found in the EEG. This is mostly used in electric contacts and PCBs coating, due to gold's electrical conductivity and tarnish-resistance features.

Aluminium (Al) is mostly concentrated in the glider's wheels, bonnet, bumpers, reinforcement pillars and suspension knuckles, as part of a lightweighting strategy. Most of the magnesium (Mg) in the glider is a primary constituent of talc (magnesium silicate), which is used as a filler in plastic components ("Interior trim & lightning" and "Exterior trim"), as well as magnesium oxide, which is present in the glider's windscreens ("Exterior glass"). Still, around 14% of the magnesium content is found in the "Steering" subsystem, as a Mg–Al alloy.

---

[7] The "Power supply" subsystem, containing the lead-acid battery, is included in the assessment to account for its essential role in supporting various functions beyond the powertrain.

Table 1 Mass distribution of selected metals present in the different subsystems of the EEG. The background colours of each metal – "Red", "Orange" and "Yellow" – represent the groups in which they are classified, as explained in the previous section.

	Tb	Dy	Ga	Nd	Pr	Sr	Pd	Ta	Ru	Cu	Sn	Ag	Au	In	Mg	Al	Mo	Nb	V	Pt	Cs	Pb	Bi
Multimedia and communication	99%	72%	69%	59%	35%	50%	54%	39%	25%	2%	14%	12%	15%	0%	6%	2%	0%	1%	0%	0%	0%	0%	0%
Doors and boot	0%	27%	30%	14%	15%	9%	0%	1%	0%	2%	3%	1%	0%	0%	3%	1%	4%	11%	5%	0%	0%	0%	0%
Steering	0%	0%	0%	24%	50%	1%	1%	0%	4%	2%	2%	2%	0%	0%	14%	4%	1%	0%	1%	0%	0%	0%	0%
Driver controls	0%	0%	1%	0%	0%	0%	14%	14%	37%	1%	5%	4%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Seating	0%	0%	0%	0%	0%	11%	1%	0%	0%	4%	6%	10%	0%	0%	2%	0%	7%	8%	6%	0%	0%	0%	0%
Electrical infrastructure	0%	0%	0%	0%	0%	0%	4%	11%	6%	71%	21%	16%	2%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%
Exterior visibility	0%	0%	0%	0%	0%	7%	1%	0%	2%	1%	4%	20%	75%	99%	0%	1%	0%	0%	0%	0%	0%	0%	0%
Exterior glass	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	10%	0%	0%	15%	0%	0%	0%	0%	0%	0%	0%	2%
Interior trim and lighting	0%	0%	0%	0%	0%	0%	1%	3%	2%	0%	1%	1%	0%	0%	13%	0%	0%	0%	0%	0%	0%	0%	0%
Exterior trim	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	20%	13%	1%	1%	2%	0%	0%	0%	0%
Wheels, tyres and accessories	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	3%	0%	0%	4%	38%	2%	0%	2%	0%	0%	0%	0%
Body structures	0%	0%	0%	0%	0%	4%	0%	0%	0%	1%	1%	0%	0%	0%	7%	16%	68%	58%	40%	0%	0%	0%	95%
Suspension, frames and mountings	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%	0%	1%	13%	11%	18%	38%	0%	0%	0%	1%
Climate	0%	0%	0%	2%	0%	1%	6%	2%	3%	2%	3%	8%	0%	0%	5%	8%	0%	0%	0%	95%	100%	0%	1%
Power supply	0%	0%	0%	0%	0%	6%	0%	0%	0%	6%	17%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	100%	0%
Restraints	1%	0%	0%	0%	0%	4%	5%	6%	4%	1%	2%	1%	1%	0%	0%	1%	1%	2%	2%	5%	0%	0%	0%
Exterior lighting	0%	0%	0%	0%	0%	2%	4%	8%	5%	2%	7%	4%	1%	0%	3%	1%	0%	0%	0%	0%	0%	0%	0%
Brake system	0%	0%	0%	0%	0%	4%	1%	3%	2%	3%	8%	1%	1%	0%	1%	1%	3%	1%	2%	0%	0%	0%	1%
Advanced driver assistance	0%	0%	0%	0%	0%	0%	4%	8%	8%	0%	2%	3%	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
Locking and security electronics	0%	0%	0%	0%	0%	0%	2%	2%	2%	0%	1%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Instrument panel and console	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	5%	0%	0%	0%	0%	0%	0%	0%	0%

The “Body structures” and “Suspension, frames & mountings” subsystems account for nearly 80% of all molybdenum (Mo), Niobium (Nb) and Vanadium (V). These metals are found as alloying elements in the high-strength steel used in various structural components. The entirety of the caesium (Cs) metal content is found in the “Climate” subsystem. Caesium is usually a constituent of non-corrosive flux, used to braze various aluminium parts. Besides caesium, the “Climate” subsystem also contains a large mass share of platinum (Pt), which is usually present in the screen-printable conductive pastes used in gas sensors [49]. It is noteworthy that the mass of platinum and caesium in the EEG amounts to a few decigrams.

Finally, almost all lead (Pb) in the glider is in the 12 V lead-acid battery, which is part of the “Power supply” subsystem. As for bismuth (Bi), it is mainly present in the paint used as a surface treatment on the glider’s body (Body structures subsystem).

Distribution of Metals in Components

The distribution of metals in components can impact the potential for reuse, recycling and substitution. Figure 3 shows the entropy (y-axis) calculated for the 23 selected metals in the EEG and the number of components in which these metals are present. As before, red, orange and yellow dots represent the metals found in the groups seen in Fig. 2. A high entropy indicates that a given metal is uniformly distributed throughout the glider. Conversely, a low entropy indicates a high concentration to a few components. Metals with a low entropy may require less effort to be separated effectively.

Copper exhibits one of the highest entropies in Fig. 3. It is present in over 700 components, mostly wire harnesses spread throughout the EEG. The high entropy indicates that

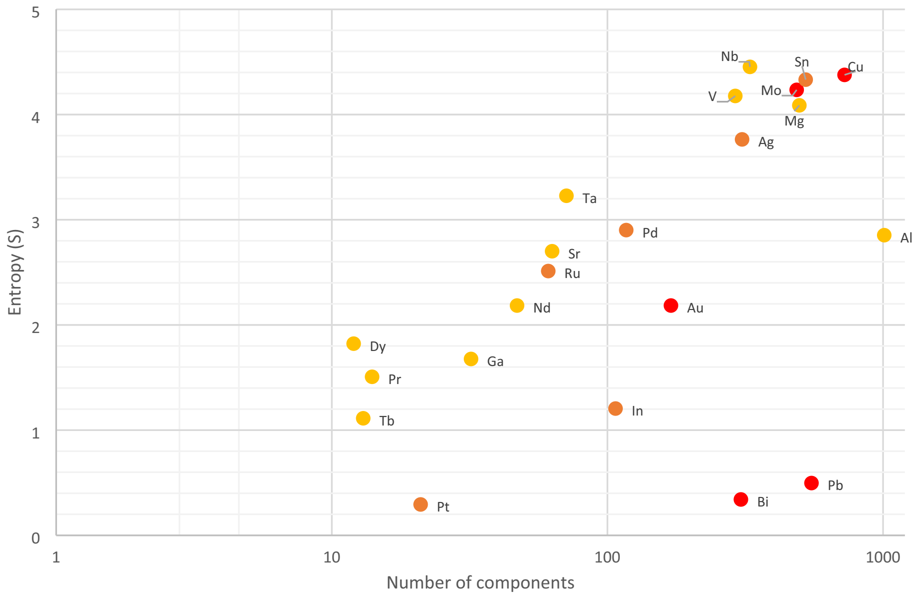

Fig. 3 Calculated entropy for selected metals in the EEG and the number of components in which these metals are present

recovering copper from the glider is a challenging task. Indeed, several studies suggest that a significant share of copper in ELVs is not functionally recycled, but “lost” to landfill, incinerator slag or as contaminants in other recycled metal flows such as steel and aluminium [50–53].

In contrast, lead, despite being present in a similar number of components (> 500), exhibits a much lower entropy than copper, as it is mostly concentrated in one component, the lead-acid battery (> 99 w-%). This greatly facilitates the separation of lead from the glider. The recycling of lead-acid batteries is a mature and well-established process, making lead one of the most recycled metals worldwide [54]. In Europe, almost 99% of all spent lead-acid batteries are recycled [55].

Despite some REMs being at risk of short-term supply disruptions, (exhibiting high DFP values, see Fig. 2), their current recovery rate from end-of-life vehicles remains minimal [19, 56]. However, Fig. 3 suggests that certain REMs might be recovered more efficiently since they are primarily concentrated in quite a small number of components. For instance, nearly all the terbium in the EEG is concentrated in just three components. Therefore, targeting the recovery of specific components could lead to improved retrieval of valuable REMs.

Although bismuth (Bi), platinum (Pt) and caesium (Cs) show relatively low entropy, their predominant use in dissipative applications such as paint, conductive paste and flux makes their recovery challenging. The same is true for the proportions of gold (Au), silver (Ag) and indium (In) embedded in mirror coatings. However, the recovery of gold and silver in electronics is challenging due to their high entropy and low overall mass in the gliders. Electric, electronic and magnetic components in ELVs are commonly shredded rather than being dismantled for recycling [19, 56].

Differences Between Gliders

The section "Metal Composition of the Gliders" noted that most metals do not show major mass variations between gliders. For half of the metals (27) found in both gliders, the mass variance is less than 10%. Consequently, most of the metals found in the SEG are grouped similarly to their EEG counterparts in the “Red”, “Orange”, “Yellow” and “Grey” categories.

However, there are exceptions. While the “Red” and “Orange” groups are composed of the same metals regardless of the equipment level, this is not the case for the “Yellow” group. Metals that are present in significantly lower quantities in the SEG compared to the EEG display a notable reduction in their short-term potential scarcity (their DFP value), as depicted in Fig. 4. The figure shows the metals that “migrate” from the “Yellow” group in the EEG to the “Grey” group in the SEG. In other words, metals whose DFP value becomes less than 5% in the SEG.

Dysprosium (Dy), terbium (Tb) and gallium (Ga) experience the largest reduction in the short-term primary metal availability indicator for a hypothetical fleet of 80 million SEGs as compared to a fleet of EEGs. A fleet of extra-equipped gliders would demand 100% of all terbium produced globally, whereas less than 0.6% of the global production of this metal would be required by a fleet of gliders with standard equipment levels. These metals are predominantly embedded in permanent magnets in the “Multimedia and communication” subsystem found in significantly larger quantities in the EEG.

In the SEG, the three metals are present in a reduced number of components. While the overall dispersion of dysprosium and terbium decreases in the SEG, the entropy of gallium

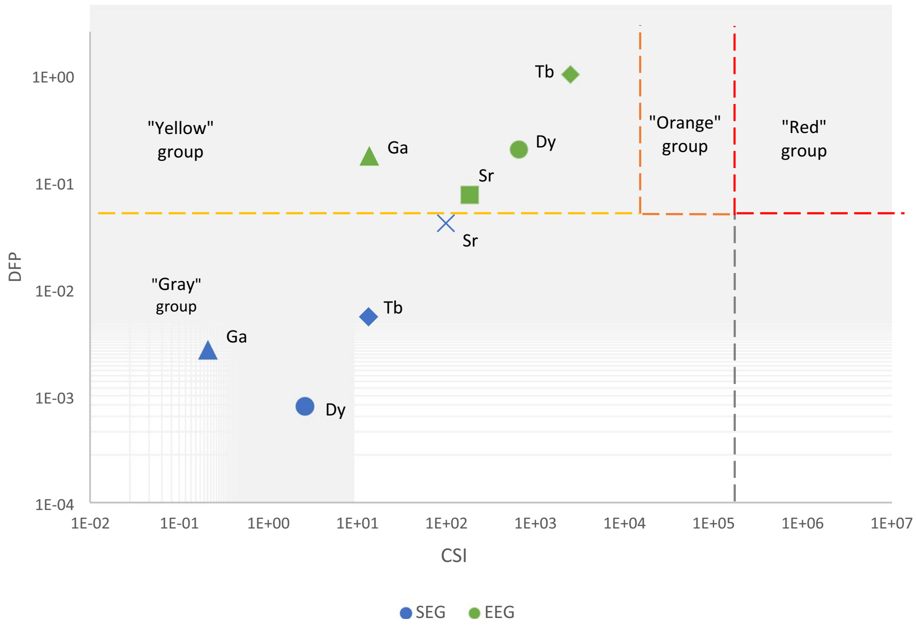

Fig. 4 Differences between gliders for selected metals. The metals depicted in the figure are those whose DFP value becomes less than 5% in the SEG, i.e., metals which "migrate" from the "Yellow" group in the ESG to the "Gray" group in the SEG

increases in this glider, as it becomes less concentrated in the components where it is present. Strontium (Sr) also transitions from the "Yellow" group in the EEG to the "Gray" group in the SEG. However, compared to dysprosium, terbium, and gallium, the mass variation between gliders is small.

The mass variation between equipment levels also impacts the long-term availability indicator, i.e., the contribution to the total CSI of the glider. However, this change is of lower interest since the affected metals are grouped in the "Yellow" category in the EEG, and their contribution to the CSI changes from small to very small. For example, the contribution of terbium to the glider's CSI changes from 0.08% in the EEG to less than 0.0005% in the SEG.

Discussion

Data Quality Analysis

The data used to inventory the metal content of the gliders is obtained from IMDS, i.e., information reported by the automotive suppliers. While some previous academic studies have reported data quality issues when using IMDS, such as duplications and omissions (data gaps) [1, 30], our analysis did not experience such issues. A key factor is that the IMDS data is complemented by information from the Volvo Cars' Vehicle Construction

Database, meaning that the IMDS data already has been thoroughly checked regarding the exact number of individual components present in each glider. Additionally, this data control also ensures that all individual components accounted for have a valid material datasheet stored in IMDS. However, even if this check is made by matching the data between the two different databases and even though the IMDS undergoes quality checks before publication, a vehicle manufacturer like Volvo Cars has limited capacity to detect possible quantitative errors in the data. This is because the information reported in the IMDS is based on the supplier's self-declaration. Thus, the data quality depends on the internal checks undertaken by each component supplier.

Moreover, in this analysis, the metal content is assessed at the elemental level. For any metal reported as being part of a compound, the content is calculated using the molecular formula provided by its CAS registry in the IMDS. If this registry is missing then best judgement is used, which may introduce some uncertainty in the results.

For the short-term potential primary metal scarcity indicator, estimating global production data for metals with missing or unreported individual production values by the USGS poses a challenge. In the case of REMs, production data is reported as an aggregate of rare-earth oxide equivalents produced in several countries. To address this, we relied on various literature sources to estimate the most common sources of REMs and their respective metal content. This introduces some uncertainty into our calculations. We investigated this by varying the production values of all assessed metals (including REMs) from -30% to + 30%. Despite the variation in production values, no REMs were reclassified from one risk group to another, suggesting that our conclusions remain consistent even with this uncertainty. Of the 55 metals assessed, only three changed groups when their production data was decreased by 30%. These three metals, Fe, Zn and Sb, were originally on the borderline between risk groups (see Fig. 2), so their reclassification is unsurprising. Accordingly, we consider these uncertainties to be minor and our findings robust in assessing the likelihood of supply disruption risks to REMs and the other metals that were assessed. Further information about this sensitivity analysis can be found in the Supplementary Information, Section G.

Metal Composition of the Gliders

The gliders' broad metal demand is a factor that contributes significantly to the supply risks of manufacturing vehicles. The gliders analysed in this study contain approximately 80% of all naturally occurring metals and metalloids in the periodic table. This is comparable to the number of metals and metalloids found in complete vehicles when the powertrain and its related components are included [29, 30]. These findings highlight the importance of considering the metal demands of systems and components outside the powertrain, when assessing the exposure of the automotive industry to supply risks. Furthermore, the broad metal demands of the automotive sector may exacerbate supply risks to other industries that rely on these metals. This underlines the need to consider other sectors when managing metal supply chains.

Interestingly, the presence of some metals in the gliders that were assessed can be attributed to the provision of specific functions in certain components. For instance, gadolinium is found in the EEG but not in the SEG, due to the use of gadolinium oxide in optical lenses present in the former. Conversely, the EEG contains less potassium than the SEG, as it has a lower mica content. Mica is a silicate mineral containing both potassium and aluminium and is commonly used in the automotive industry for its thermal and electrical insulation properties. However, in the EEG, alternative insulation materials substitute some of the mica, due to the presence of a panoramic roof in this glider.

Assessment of Short and Long-term Potential Primary Metal Scarcity

Based on the indicators used in this study, it is possible to identify metals that are at risk of supply constraints, in terms of both short and long-term availability. However, when interpreting the results, it is important to consider additional aspects. For instance, the short-term potential scarcity indicator relies solely on primary production and does not account for the availability of metals from secondary sources, which can be substantial for some metals. This may lead to overestimating the risk to such metals as lead, for which a significant proportion of global production comes from secondary sources.

To examine the impact of secondary production on the results, additional calculations were made which included the proportion of production from secondary sources for metals in the “Red,” “Orange,” and “Yellow” groups. Notably, the ranking of metals in terms of short-term potential scarcity did not change significantly when considering secondary production. This analysis is available under Supplementary Information, Section G. It suggests that the results are robust and not significantly influenced by the potential bias introduced by not accounting for secondary production in calculating the indicator. This is easily understood since recycling rates would need to exceed 90% before secondary supply would increase total supply by an order of magnitude (and move a metal noticeably in the diagram in Fig. 2).

This study uses the CSI to provide a long-term perspective on potential metal scarcity in the gliders. Although the CSI is a suitable long-term resource impact assessment method for the setup of this study, it does have limitations. Firstly, the CSI only accounts for resources found in the Earth’s crust and does not consider other environmental compartments like oceans. These contain significant amounts of some elements that are relevant to the automotive industry, such as sodium, magnesium and potassium. In this study, this limitation may result in a slight overestimation of the long-term potential scarcity of such elements which are (or could be) economically extracted from seawater. Secondly, the CSI’s focus on elemental scarcity means that it does not consider the resource scarcity of the various chemical forms in which the element occurs, such as different minerals or mineral compounds. This may pose a challenge when a compound is considered scarce, even though its constituent elements are not. This limitation is reflected in the fact that this study conducted its assessment at the elemental level, despite some compounds (like mica) being used by the automotive industry for their compound properties rather than those of their elements.

While some metals show significant supply risks in the short and long term, it is important to consider the usage trends of such metals in the automotive industry and other sectors, to further understand the potential impact of these risks. Among the metals assessed, gold stands out as being at the greatest risk of potential long-term scarcity. It is used as a coating and in bonding wires in many electronic components. As the presence of electronic equipment in cars increases [13, 19, 20], the demand for gold in the automotive industry may exacerbate supply constraints associated with its short and long-term potential scarcity.

Another metal of interest is bismuth, as its global demand is expected to increase by 4–5% annually, primarily due to its rising use in the pharmaceutical sector [8]. In the automotive industry, bismuth can be found as a pigment in paints used for surface treatment. However, increased demand for bismuth in other sectors could result in supply challenges for the automotive industry due to competition. In such a scenario, a potential solution to mitigate the risks associated with elevated potential scarcity is to adopt a substitution strategy, using other pigments not based on bismuth [57].

Molybdenum is used primarily as an alloying agent in various types of steels and as a catalyst in industrial applications. According to a report by the European Commission [58], demand for molybdenum is expected to grow in the coming years, mainly due to increased demand for infrastructure spending and oil and gas drilling activity. In the automotive industry, molybdenum plays a crucial role as an alloying agent in high-strength steels. These are used to reduce weight and improve fuel economy and safety. However, there are limited options for substituting molybdenum as an alloying agent in steels [58, 59]. Although a significant share of molybdenum can be functionally recycled from ELVs [56], the overall recycling efficiency of molybdenum from other sectors is not expected to increase significantly while the market value of primary molybdenum remains low [58]. Hence, as demand for molybdenum increases in other sectors, the automotive industry needs to seek solutions that avoid short-term supply risks.

This study shows that lead is at considerable risk of supply disruptions, meaning that it is subject to potential scarcity in both the short and long term. The automotive sector is the largest consumer of lead, as it is a fundamental raw material in lead-acid batteries [58, 60]. Globally, some 40% of all lead produced annually is derived from primary sources, despite it having one of the highest recycling rates of all materials in common use [58, 61]. In the short term, the demand for lead-acid batteries is expected to increase, as these batteries are commonly used as storage devices in 12 V or 48 V (“low voltage”) electrical systems in conventional as well as new electrified vehicles [58, 62, 63]. In future electric vehicle platform designs, batteries for low-voltage electrical systems may be phased out entirely, relying solely on voltage conversion from a larger, high-voltage traction battery (such as a lithium-ion battery pack) and by using power electronics. However, to achieve commonality across several vehicle models using the same platform design and the same low-voltage electrical systems and to include an energy buffer for redundancy, a smaller, separate, low-voltage battery may remain a viable solution. For this purpose, lead-acid batteries remain a cost-effective option [63, 64]. On the other hand, environmental and health concerns have raised questions about the continued use of lead in vehicles [64] and improvements in other, lead-free battery technologies may eventually push lead-based options out of the market, even for low-voltage systems [63, 65]. This may result in a decreased long-term presence of lead in vehicles.

Our assessment shows that copper is at risk of supply constraints in both the short and long term. Besides being commonly used in various types of wiring, copper plays an essential role in low-carbon technologies, such as those used in the transport and energy sectors [58]. Although copper products can be recycled without any loss in properties, the current demand for copper is met mainly by primary sources [58]. The trend towards electrification and increased use of electronic components in the automotive industry is also making copper more prevalent [58, 66, 67]. This may worsen the supply constraints associated with the short and long-term availability of copper.

Similarly, REMs are crucial to several industrial applications, including magnets, catalysts and polishing compounds. The annual average growth rate of REM consumption is expected to range from 5 to 10% through 2025, with the magnet materials sector expected to have higher than average growth [68]. In this study, the assessment of REMs does not reveal significant supply risks for most of the metals in the short or long term. However, the study identified four REMs (terbium, neodymium, dysprosium and praseodymium) that show elevated short-term supply risks. For instance, our assessment reveals that if the global fleet of vehicles being produced every year was solely comprised by the extra-equipped glider we analysed, the demand for terbium would surpass the total global production. This finding demands attention, especially considering that we have sidestepped the traction motor of electric powertrains, which could demand terbium in magnets. Such insights highlight a potential internal competition within the automotive industry, where multiple trends might be inadvertently escalating the demand for the same metals. As the automotive industry continues to transition towards electrification, the demand for these specific metals is expected to increase [8, 68]. It is essential for the industry to recognize and reconcile these competing trends to ensure a resilient metal supply chain for the future.

The implications of our findings on metal scarcity, while rooted in the automotive industry, are far-reaching and could be extended beyond this sector. The move towards renewable energy systems and new mobility solutions put additional pressure on the same finite metal resources. For instance, the expansion of wind power may intensify the demand for REMs, and electrification in general may increase the demand for copper [69]. The infrastructure required to support a shift to electric vehicles – including charging stations and grid storage solutions – further underscores the need of addressing metal scarcity across different sectors [70, 71].

The extension of our findings into broader industrial sectors leads to a consideration of other factors influencing metal scarcity. While our assessment primarily focuses on the physical availability of metals, it is important to acknowledge that metal sourcing is influenced by many environmental, social, and geopolitical factors influencing the dynamics of supply and demand. For instance, the social and environmental repercussions of extracting e.g., cobalt, gold and silver, especially in developing countries, pose significant challenges that extend beyond the physical availability of metals [72–77]. Similarly, the geopolitical landscape influences the stability of metal supplies, with political unrest and trade policies impacting supply chains of key metals used in the automotive industry [78–80]. Future research is encouraged to expand the scope of investigation to include such aspects.

Distribution of Metals in the Gliders

Our results reveal that the distribution of metals varies greatly across the assessed subsystems. Among those, the “Multimedia and communication” subsystem contains a large share of the mass of REMs in the gliders, such as terbium, dysprosium, neodymium and praseodymium. This is mainly due to the presence of permanent magnets in the sound system.

The low mass of REMs, combined with their low economic value and relatively low concentration in individual components in the gliders, presents significant challenges for their effective recovery from ELVs [8, 56]. However, certain REMs (such as dysprosium and terbium) exhibit a concentrated distribution across a small number of components, thus presenting a potential opportunity for improving their recovery in the assessed gliders. Therefore, targeting the recovery of specific components could lead to an improved recovery of valuable REMs.

The study also found that the “Exterior visibility” and “Electrical infrastructure” subsystems contain a significant proportion of gold, silver and copper. This makes them potentially vulnerable to supply risks in both the short and long term. The recovery of many precious metals in the gliders might be challenging due to their relatively high entropy and low overall mass. In this case, a potential strategy for improving the recovery of precious metals like gold and silver from electronics could be to target the separation of specific components with larger concentrations of such metals from, say, PCBs. However, it is also important to note that a considerable share of these metals is used in dissipative applications, making it difficult to recover them cost-effectively [81]. As stated before, this is also the case for bismuth, which is present in paint pigments. In this case, adopting alternative pigments could mitigate supply risks in the automotive industry arising from a potential scarcity of bismuth.

Our assessment highlights significant challenges in recovering copper effectively from ELVs due to its high entropy. Studies indicate that the recovery rate of copper from ELVs is relatively low, at around 50% [82, 83]. This underlines the difficulty involved in separating copper from other material streams, as it is distributed across many components throughout the glider, primarily in the form of wire harnesses. Processing wire harnesses from ELVs is challenging due to the heterogeneity of cable assemblies. Depending on the recycling strategy chosen, the recovery process could involve the use of large amounts of solvents or thermal energy [84, 85]. Moreover, manually removing wire harnesses from ELVs may not be economically viable, further complicating copper recovery [50]. Nevertheless, the development of new techniques for recycling non-uniform waste wire harnesses might improve the recovery of copper from ELVs in the future [85–87].

In contrast, lead is characterised by a relatively low entropy, primarily due to its large concentration in one component, the lead-acid battery. This characteristic suggests that lead recovery from ELVs requires comparatively less effort than metals with higher entropy, such as copper. Indeed, recycling rates of lead-acid batteries exceeding 95% have been observed in Europe and the United States, indicating the viability and effectiveness of lead recovery [55, 88]. However, reports from China, another large market, indicate significant challenges in achieving comparable recycling rates [89].

Furthermore, the study revealed that equipment levels do not significantly impact potential long-term primary metal scarcity. The same set of metals that display considerable long-term supply risk (e.g., gold and copper) appears in similar amounts in both gliders. However, differences in equipment levels do show significant variations in the short-term potential scarcity of some metals. For instance, the EEG shows a significant increase in the short-term potential scarcity of three metals, dysprosium, terbium and gallium, due to a larger presence of permanent magnets in this glider. This highlights the need for more sustainable solutions, such as substitution (with, e.g., iron-based permanent magnets) or more efficient recovery processes from ELVs.

While the gliders analysed in this study might be “over-equipped” compared to some other vehicles in the same segment, trends in the automotive industry show a consistent increase in equipment levels [13, 19, 20]. From a metal scarcity perspective, these trends could result in a narrowing gap between standard cars and extra-equipped ones. Driving this evolution are new requirements for safety, comfort, digital connectivity, and automation, leading to a rising demand for potentially scarce metals.

Given the challenges associated with these trends and their potential for increasing the supply risks for certain metals, the automotive industry must explore solutions to mitigate those risks. Solutions may include substitution, more efficient recovery processes from ELVs, or other strategies that could reduce the use of scarce metals.

Conclusions

This study provides a comprehensive assessment of the metal composition of vehicle gliders and evaluates the short and long-term potential scarcity of primary metals for the automotive industry. The results demonstrate that the broad metal demand of the gliders contributes significantly to supply risks related to vehicle manufacturing.

Our findings reveal that gold, bismuth, molybdenum, copper, lead and certain REMs face the highest scarcity risks. The increasing integration of electronic components in vehicles is likely to amplify these risks, a concern that our analysis on metal distribution across subsystems illustrates. For instance, the substantial amounts of REMs used in entertainment and communication equipment, as well as precious metals in other components, present distinct challenges but also some opportunities for targeted recovery or substitution strategies. Moreover, the potential for economic recovery and substitution of metals, including copper, REMs, and precious metals, may be hindered by a high degree of dispersion over many components.

In conclusion, the results of this study emphasizes the importance of considering metal requirements beyond the powertrain when evaluating the automotive industry's exposure to supply risks, and the industry's role in contributing to metal scarcity in society.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43615-024-00353-x.

Acknowledgements The authors gratefully acknowledge the financial support from the following funding bodies: VINNOVA, the Swedish Government Agency for Innovation Systems and the Swedish Energy Agency (Energimyndigheten), through the Strategic Vehicle Research and Innovation (FFI) programme.

Authors' Contributions Conceptualization: FBO, AN, MB, BS; Data curation: FBO; Methodology: FBO, AN, MB, BS; Formal analysis and investigation: FBO; Writing—original draft preparation: FBO; Writing—review and editing: FBO, AN, MB, BS; Project administration: FBO, MB, AN, BS; Validation: AN; Supervision: MB, AN, BS.

Funding Open access funding provided by Chalmers University of Technology. VINNOVA, the Swedish Government Agency for Innovation Systems and the Swedish Energy Agency (Energimyndigheten), through the Strategic Vehicle Research and Innovation (FFI) programme.

Data Availability Available in Supporting Information.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Felipe Bitencourt de Oliveira and Maria Bernander are employed by Volvo Car Corporation.

References

1. Field FR III, Wallington TJ, Everson M, Kirchain RE (2017) Strategic materials in the automobile: a comprehensive assessment of strategic and minor metals use in passenger cars and light trucks. Environ Sci Technol 51(24):14436–14444. https://doi.org/10.1021/acs.est.6b06063
2. Ortego A, Calvo G, Valero A, Iglesias-Émbil M, Valero A, Villacampa M (2020) Assessment of strategic raw materials in the automobile sector. Resour Conserv Recycl 161:104968. https://doi.org/10.1016/j.resconrec.2020.104968
3. OICA (2022) "Statistics". [Online]. Available: https://www.oica.net/category/production-statistics/2022-statistics/. Accessed 09 02 2023
4. Drive Sustainability (2018) "Material change - A study of risks and opportunities for collective action in the materials supply chains of the automotive and electronic industries". [Online]. Available: https://drivesustainability.org/wp-content/uploads/2018/07/Material-Change_VF.pdf. Accessed 09 February 2023
5. Öko-Institut (2018) "Ensuring a sustainable supply of raw materials for electric vehicles - a synthesis paper on raw material needs for batteries". [Online]. Available: https://www.agora-verkehrswende.de/fileadmin/Projekte/2017/Nachhaltige_Rohstoffversorgung_Elektromobilitaet/Agora_Verkehrswende_Rohstoffestrategien_EN_WEB.pdf. Accessed 09 February 2023
6. Lèbre É, Stringer M, Svobodova K, Owen J, Kemp D, Côte C, Arratia-Solar A, Valenta R (2020) The social and environmental complexities of extracting energy transition metals. Nat Commun 11:4823. https://doi.org/10.1038/s41467-020-18661-9
7. Earth O (2021) Sustainable opportunities for critical metals. One Earth 4(2021):327–330
8. European Commission (2020) "Study on the EU's list of critical raw materials''. Factsheets on critical raw materials," Publications Office of the European Union, Luxembourg, 2020.https://data.europa.eu/doi/10.2873/11619
9. Volkswagen Group (2022) "Responsible raw materials report 2021". [Online]. Available: https://www.volkswagenag.com/presence/nachhaltigkeit/documents/supply-chain/Volkswagen-Group-Responsible-Raw-Materials-Report-2021.pdf. Accessed 09 February 2023
10. Lewis GM, Buchanan CA, Jhaveri KD, Sullivan JL, Kelly JC, Das S, Taub AI, Keoleian GA (2019) Green principles for vehicle lightweighting. Environ Sci Technol 53(8):4063–4077. https://doi.org/10.1021/acs.est.8b05897
11. Restrepo E, Løvik AN, Widmer R, Wäger P, Müller DB (2019) "Historical penetration patterns of automobile electronic control systems and implications for critical raw materials recycling," Resources 58(8). https://doi.org/10.3390/resources8020058
12. European Commission (2022) "New rules to improve road safety and enable fully driverless vehicles in the EU". [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_4312. Accessed 10 February 2023
13. Trovão JP (2022) The vehicle industry is moving fast. IEEE Veh Technol Mag 17(1):98–107. https://doi.org/10.1109/MVT.2021.3130399
14. Arowosola A, Gaustad G (2019) Estimating increasing diversity and dissipative loss of critical metals in the aluminum automotive sector. Resour Conserv Recycl 150:104382. https://doi.org/10.1016/j.resconrec.2019.06.016
15. Theyssier M-C (2015) Manufacturing of advanced high-strength steels (AHSS). In: Shome M, Tumuluru M (eds) Welding and joining of advanced high strength steels (AHSS): The automotive industry. Woodhead Publishing, Cambridge, pp 29–53. https://doi.org/10.1016/B978-0-85709-436-0.00003-5
16. Pehlken A, Albach S, Vogt T (2017) Is there a resource constraint related to lithium ion batteries in cars? Int J Life Cycle Assess 22(2017):40–53. https://doi.org/10.1007/s11367-015-0925-4
17. Lee J, Bazilian MD, Sovacool B, Hund K, Jowitt SM, Nguyen TP, Månberger A, Kah M, Greene S, Galeazzi C, Awuah-Offei K, Moats M, Tilton J, Kukoda S (2020) Reviewing the material and metal security of low-carbon energy transitions. Renew Sustain Energy Rev 124(2020):109789. https://doi.org/10.1016/j.rser.2020.109789
18. Nguyen RT, Baek DL, Haile BJ, Case ME, Cole CC, Severson MH, Carlson LN (2020) Critical material content in modern conventional U.S. vehicle electronics. Waste Manage 109(2020):10–18. https://doi.org/10.1016/j.wasman.2020.04.040
19. Restrepo E, Løvik AN, Wäger P, Widmer R, Lonka R, Müller DB (2017) Stocks, flows, and distribution of critical metals in embedded electronics in passenger vehicles. Environ Sci Technol 51(3):1129–1139. https://doi.org/10.1021/acs.est.6b05743

20. PwC (2013) "Spotlight on automotive - PwC semiconductor report". [Online]. Available: https://www.pwc.com/gx/en/technology/publications/assets/pwc-semiconductor-survey-interactive.pdf. Accessed 13 February 2023
21. Henstock ME (1988) The impacts of materials substitution on the recyclability of automobiles. Resour Conserv Recycl 2(1):69–85. https://doi.org/10.1016/0921-3449(88)90037-7
22. Ginley DM (1994) Material flows in the transport industry: An example of industrial metabolism. Resour Policy 20(3):169–181. https://doi.org/10.1016/0301-4207(94)90049-3
23 Das S, Randall Curlee T, Rizy CG, Schexnayder SM (1995) Automobile recycling in the United States: Energy impacts and waste generation. Resources, Conserv Recycl 14(3–4):265–284. https://doi.org/10.1016/0921-3449(95)00021-A
24. Alonso E, Field FR, Kirchain RE (2012) Platinum availability for future automotive technologies. Environ Sci Technol 46(23):12986–12993. https://doi.org/10.1021/es301110e
25. Alonso E, Wallington T, Sherman A, Everson M, Field F, Roth R, Kirchain R (2012) An assessment of the rare earth element content of conventional and electric vehicles. SAE Int J Mater Manuf 5(2):473–477. https://doi.org/10.4271/2012-01-1061
26. Zhang J, Everson MP, Wallington TJ, Field FR III, Roth R, Kirchain RE (2016) Assessing economic modulation of future critical materials use: the case of automotive-related platinum group metals. Environ Sci Technol 50(14):7687–7695. https://doi.org/10.1021/acs.est.5b04654
27. Schmid M (2020) Challenges to the European automotive industry in securing critical raw materials for electric mobility: the case of rare earths. Mineral Mag 84(1):5–17. https://doi.org/10.1180/mgm.2020.9
28. Ortego A, Valero A, Valero A, Restrepo E (2018) Vehicles and critical raw materials: a sustainability assessment using thermodynamic rarity. J Ind Ecol 22(5):1005–1015. https://doi.org/10.1111/jiec.12737
29. Iglesias-Émbil M, Valero A, Ortego A, Villacampa M, Vilaró J, Villalba G (2020) Raw material use in a battery electric car – a thermodynamic rarity assessment. Resour Conserv Recycl 158(2020):104820. https://doi.org/10.1016/j.resconrec.2020.104820
30. Bhuwalka K, Field FR III, De Kleine RD, Kim HC, Wallington TJ, Kirchain RE (2021) Characterizing the changes in material use due to vehicle electrification. Environ Sci Technol 55(14):10097–10107. https://doi.org/10.1021/acs.est.1c00970
31. Widmer R, Du X, Haag O, Restrepo E, Wägner PA (2015) Scarce metals in conventional passenger vehicles and end-of-life vehicle shredder output. Environ Sci Technol 49(7):4591–4599. https://doi.org/10.1021/es505415d
32. Knobloch V, Zimmermann T, Gößling-Reisemann S (2018) From criticality to vulnerability of resource supply: The case of the automobile industry. Resour Conserv Recycl 138(2018):272–282. https://doi.org/10.1016/j.resconrec.2018.05.027
33. Jasiński D, Cinelli M, Dias LC, Meredith J, Kirwan K (2018) Assessing supply risks for non-fossil mineral resources via multi-criteria decision analysis. Resources Policy 58(October 2018):150–158. https://doi.org/10.1016/j.resourpol.2018.04.011
34. Henßler M, Bach V, Berger M, Finkbeiner M, Ruhland K (2016) Resource efficiency assessment—comparing a plug-in hybrid with a conventional combustion engine. Resources 5(1):5. https://doi.org/10.3390/resources5010005
35. André H, Ljunggren M (2022) Short and long-term mineral resource scarcity impacts for a car manufacturer: The case of electric traction motors. J Clean Prod 361(2022):1321–1340. https://doi.org/10.1016/j.jclepro.2022.132140
36. Achzet B, Helbig C (2013) How to evaluate raw materials supply risks — an overview. Resour Policy 38(2013):435–447. https://doi.org/10.1016/j.resourpol.2013.06.003
37 Arvidsson R, LjunggrenSöderman M, Sandén BA, Nordelöf A, André H, Tillman A-M (2020) A crustal scarcity indicator for long-term global elemental resource assessment in LCA. Int J Life Cycle Assess 25(2020):1805–1817. https://doi.org/10.1007/s11367-020-01781-1
38. Andersson BA (2000) Materials availability for large-scale thin-film photovoltaics. Prog Photovoltaics Res Appl 8(1):61–76. https://doi.org/10.1002/(SICI)1099-159X(200001/02)8:1%3c61::AID-PIP301%3e3.0.CO;2-6
39. ACEA (2022) "The Automobile Industry Pocket Guide 2022/2023". [Online]. Available: https://www.acea.auto/files/ACEA_Pocket_Guide_2022-2023.pdf. Accessed 14 February 2023
40. DXC Technology (2021) "DXC international material data system (IMDS)". [Online]. Available: https://public.mdsystem.com/documents/10906/633283/DXC_IMDS_Making_Manufacturers_Greener_A4.pdf/3251a31d-b1d0-215b-ddac-eea47bc575dc?t=1631695498082. Accessed 14 February 2023

41. Bitencourt de Oliveira F, Nordelöf A, Sandén BA, Widerberg A, Tillman A-M (2022) Exploring automotive supplier data in life cycle assessment – precision versus workload. Transp Res Part D: Transpo Environ 105(April 2022):103247. https://doi.org/10.1016/j.trd.2022.103247
42. DXC Technology (2022) "Material data system (IMDS) user manual version 13.2". [Online]. Available: https://public.mdsystem.com/documents/10906/16811/imds_usermanual_13.2_en.pdf/5a737c0f-3819-8929-cac3-94e7ecefc051?t=1650979884928. Accessed 14 February 2023
43. ACEA (2023) "World passenger car production". [Online]. Available: https://www.acea.auto/figure/world-passenger-car-production/. Accessed 18 12 2023
44. U.S. Geological Survey (2023) "Commodity statistics and information". [Online]. Available: https://www.usgs.gov/centers/national-minerals-information-center/commodity-statistics-and-information. Accessed 17 12 2023
45. van Oers L, Guinée JB, Heijungs R (2020) Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. Int J Life Cycle Assess 25:294–308. https://doi.org/10.1007/s11367-019-01683-x
46. Vieira MDM, Goedkoop MJ, Storm P, Huijbregts MAJ (2012) Ore grade decrease as life cycle impact indicator for metal scarcity: the case of copper. Environ Sci Technol 46(23):12772–12778. https://doi.org/10.1021/es302721t
47. Sethna J (2006) Entropy. In: Press OU (ed) Statistical mechanics: entropy, order parameters and complexity. Oxford University Press, Oxford, pp 77–104
48. Tanaka (2023) "Precious metals support the future of automobiles". [Online]. Available: https://tanaka-preciousmetals.com/en/solution/main-product/automobiles/. Accessed 06 April 2023
49. Heraeus (2023) "Sensor pastes". [Online]. Available: https://www.heraeus.com/en/het/products_and_solutions_het/thick_film_materials/sensor_pastes_electronics/sensor_pastes_page.html. Accessed 06 April 2023
50. Center for Automotive Research (2006) "Copper in end-of-life vehicle recycling". [Online]. Available: https://www.cargroup.org/wp-content/uploads/2017/02/Copper-in-End_of_Life-Vehicle-Recycling.pdf. Accessed 20 February 2023
51. Simic V, Dimitrijevic B (2012) Production planning for vehicle recycling factories in the EU legislative and global business environments. Resour Conserv Recycl 60(2012):78–88. https://doi.org/10.1016/j.resconrec.2011.11.012
52 Fonseca AS, Nunes MI, Arlindo Matos M, Gomes AP (2013) Environmental impacts of end-of-life vehicles' management: recovery versus elimination. Int J Life Cycle Assess 18(August 2013):1374–1385. https://doi.org/10.1007/s11367-013-0585-1
53. Tasala Gradin K, Luttropp C, Björklund A (2013) Investigating improved vehicle dismantling and fragmentation technology. J Clean Prod 54(September 2013):23–29. https://doi.org/10.1016/j.jclepro.2013.05.023
54. Ballantyne AD, Hallett JP, Riley JD, Shah N, Payne DD (2018) Lead acid battery recycling for the twenty-first century. R Soc Open Sci 5:171368. https://doi.org/10.1098/rsos.171368
55. Markit HIS (2020) "An analysis of EU collection and recycling of lead-based automotive batteries during the period 2015–2017". [Online]. Available: https://www.acea.auto/files/ES-RECYCLING-V10.pdf. Accessed 20 February 2023
56 Andersson M, LjunggrenSöderman M, Sandén BA (2017) Are scarce metals in cars functionally recycled? Waste Manag 60(2017):407–416. https://doi.org/10.1016/j.wasman.2016.06.031
57. U.S. Geological Survey (2023a) "Mineral commodity summaries - Bismuth". [Online]. Available: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-bismuth.pdf. Accessed 29 March 2023
58. European Commission (2020) "Study on the EU's list of critical raw materials. Non-critical raw materials factsheets", Publications Office of the European Union, Luxembourg, 2020.
59. U.S. Geological Survey (2021) "2018 minerals yearbook - molybdenum". [Online]. Available: https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2018-moly.pdf. Accessed 04 April 2023
60. U.S. Geological Survey (2021) "2017 minerals yearbook - lead". [Online]. Available: https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2017-lead.pdf. Accessed 04 April 2023
61. ILZSG, International Lead and Zinc Study Group - Lead and Zinc Statistics (2022) [Online]. Available: www.ilzsg.org/free-access-data/. Accessed 04 April 2023
62. Day L (2021) "Why electric cars still use ordinary 12-volt batteries". [Online]. Available: https://jalopnik.com/why-electric-cars-still-use-ordinary-12-volt-batteries-1847209291. Accessed 04 April 2023
63. ITRI (2017) "Lead-acid batteries - impact on future tin use", Technical Report 2017, International Tin Association, Frogmore, UK

64. Gensch C-O, Baron Y, Moch K (2016) "8th Adaptation to scientific and technical progress of exemptions 2(c), 3 and 5 of Annex II to Directive 2000/53/EC (ELV)". [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/e41f365a-f74e-11e7-b8f5-01aa75ed71a1/language-en. Accessed 04 April 2023
65. Moseley PT, Rand DA, Garche J (2017) "Lead-acid batteries for future Automobiles: status and prospects". In Lead-acid batteries for future Automobiles. Elsevier, pp 601-618
66. CDA, Copper Development Association Inc. - Copper Facts - Transportation and Industry (2022) [Online]. Available: https://copper.org/education/c-facts/. Accessed 29 March 2023
67. OSVehicle (2022) "How much copper wire is in an electric car?". [Online]. Available: https://www.osvehicle.com/how-much-copper-wire-is-in-an-electric-car/. Accessed 29 March 2023
68. U.S. Geological Survey (2022) "2018 minerals yearbook - rare earths". [Online]. Available: https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-rare-earths.pdf. Accessed 29 March 2023
69. International Renewable Energy Agency (2022) “7.3 Demand for critical materials”. In World Energy Transitions Outlook 2022 - 1.5°C Pathway, International Renewable Energy Agency, IRENA, 2022, pp 290–333
70. Raghavan Srinivasa S, Nordelöf A, Ljunggren M, Arvidsson R (2023) Metal requirements for road-based electromobility transitions in Sweden. Resour Conserv Recycl 190(2023):106777. https://doi.org/10.1016/j.resconrec.2022.106777
71. Prettico G, De Paola A, Thomas D, Andreadou N, Papaiannou I, Kotsakis E (2022) Clean energy technology observatory: smart grids in the European Union – 2022 status report on technology development trends, value chains and markets. Publications Office of the European Union, Luxembourg
72. Gulley AL (2023) China, the democratic Republic of the Congo, and artisanal cobalt mining from 2000 through 2020. PNAS 120(26):e2212037120. https://doi.org/10.1073/pnas.2212037120
73. Córdoba-Tovar L, Marrugo-Negrete J, Ramos Barón PA, Díez S (2023) Ecological and human health risk from exposure to contaminated sediments in a tropical river impacted by gold mining in Colombia. Environ Res 236(2023):116759. https://doi.org/10.1016/j.envres.2023.116759
74. Collyns D (2023) “Poisoned for decades by a Peruvian mine, communities say they feel forgotten.” Mongabay. [Online]. Available: https://news.mongabay.com/2023/11/poisoned-for-decades-by-a-peruvian-mine-communities-say-they-feel-forgotten/. Accessed 02 November 2023
75. Cacciuttolo C, Cano D (2022) Environmental impact assessment of mine tailings spill considering metallurgical processes of gold and copper mining: case studies in the Andean countries of Chile and Peru. Water 14(19):3057. https://doi.org/10.3390/w14193057
76. Fandiño Piñeiro X, Ave MT, Mallah N, Caamaño-Isorna F, NuriaGuisández Jiménez A, Nuno Vieira D, Bianchini F, Muñoz-Barús JI (2021) Heavy metal contamination in Peru: implications on children’s health. Sci Rep 11(2021):22729. https://doi.org/10.1038/s41598-021-02163-9
77. Berg RC, Ziemer H, Kohan A (2021) “A closer look at colombia’s illegal, artisanal, and small-scale mining” Center for strategic and international studies. [Online]. Available: https://www.csis.org/analysis/closer-look-colombias-illegal-artisanal-and-small-scale-mining. Accessed 02 November 2023
78. Jones B, Nguyen-Tien V, Elliot RJR (2022) The electric vehicle revolution: Critical material supply chains, trade and development. World Econ 46(1):2–26. https://doi.org/10.1111/twec.13345
79. Silberg G (2022) “The impact of the Russia-Ukraine war on the auto industry”. [Online]. Available: https://kpmg.com/kpmg-us/content/dam/kpmg/pdf/2023/impact-auto-industry.pdf. Accessed 17 December 2023
80. U.S. Department of Energy (2020) “Critical materials rare earths supply chain: a situational white paper,” Off Energy Efficiency Renew Energy
81. Jacoby M (2022) "Chemical and engineering news - automotive glass presents unique challenges for manufacturing and recycling". [Online]. Available: https://cen.acs.org/materials/inorganic-chemistry/Automotive-glass-manufacturing-and-recycling-presents-unique-challenges/100/i14. Accessed 25 April 2023
82. Ruhrberg M (2006) Assessing the recycling efficiency of copper from end-of-life products in Western Europe. Resour Conserv Recycl 48(2):141–165. https://doi.org/10.1016/j.resconrec.2006.01.003
83. Wang T, Berrill P, Zimmerman JB, Hertwich EG (2021) Copper recycling flow model for the United States economy: impact of scrap quality on potential energy benefit. Environ Sci Technol 55(8):5485–5495. https://doi.org/10.1021/acs.est.0c08227
84. Kumar H, Kumagai S, Kameda T, Saito Y, Yoshioka T (2020) Simultaneous recovery of high-purity Cu and poly(vinyl chloride) from waste wire harness via swelling followed by ball milling. Sci Rep 10(10754):2020. https://doi.org/10.1038/s41598-020-67795-9

85. Kumar H, Kumagai S, Kameda T, Saito Y, Yoshioka T (2021) One-pot wet ball-milling for waste wire-harness recycling. J Mater Cycles Waste Manage 23(2021):461–469. https://doi.org/10.1007/s10163-020-01163-7
86. Lu J, Xu J, Kumagai S, Kameda T, Saito Y, Yoshioka T (2019) Separation mechanism of polyvinyl chloride and copper components from swollen electric cables by mechanical agitation. Waste Manag 93(15 June 2019):54–62. https://doi.org/10.1016/j.wasman.2019.05.024
87. Xu J, Kumagai S, Kameda T, Saito Y, Takahashi K, Hayashi H, Yoshioka T (2019) Separation of copper and polyvinyl chloride from thin waste electric cables: A combined PVC-swelling and centrifugal approach. Waste Manag 89(15 April 2019):27–36. https://doi.org/10.1016/j.wasman.2019.03.049
88. Smith Bucklin Statistics Group (2020) "National recycling rate study". [Online]. Available: https://batterycouncil.org/wp-content/uploads/2019/11/BCI_433784-19_RecyclingRateStudy_19Update_FINAL.pdf. Accessed 25 April 2023
89. Sun Z, Cao H, Zhang X, Lin X, Zheng W, Cao G, Sun Y, Zhang Y (2017) Spent lead-acid battery recycling in China – A review and sustainable analyses on mass flow of lead. Waste Manag 64(June 2017):190–201. https://doi.org/10.1016/j.wasman.2017.03.007