Life cycle assessment of gold:

Comparative evaluation of primary and secondary production

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Abstract

Gold has been coveted for millennia and is often associated with wealth, power, and security. However, the production of gold has substantial environmental impacts. Resource depletion, the extensive use of potentially dangerous chemicals, such as cyanide or mercury, toxic emissions, land use change, and high energy consumption, just to name a few. The relevancy of the environmental impact of gold mining is highlighted by the fact that gold is the raw material with the most individual mines in the world.

The life cycle assessment (LCA) method, which assesses environmentally relevant material flows along the entire life cycle of products as well as services, is suitable for quantifying and analyzing the environmental impacts in various categories for a product like gold. This study analyzes the most important production routes for gold—industrial gold and copper mining, artisanal and small-scale mining (ASM), high-value recycling, and waste from electrical and electronic equipment (WEEE)—using the LCA method.

Thorough literature research revealed that gold originating from ASM and high-value recycling is not included in common LCA databases. Additionally, there are substantial data gaps concerning industrial mining, which are frequently addressed through simplified extrapolations referred to as intersystemic data scaling (IDS).

A methodological study was conducted to analyze the problem of multi-product allocation in LCA, using a Finnish copper mine as a prime example. Various allocation methods were applied and discussed with regard to their suitability. It was found that a stronger focus should be put on the benefit of a product system instead of using strict hierarchies valuing one allocation method as generally advanced over another.

To address the absence of data on gold from ASM in LCA databases, a comprehensive collection of over 100 data sets from 47 ASM mines in the Brazilian Amazon was conducted. These data sets encompassed energy and mercury utilization. Despite the implementation of retorts for mercury recycling, an annual release of approximately 2.5 tons of mercury is observed in the region. The energy requirements and the associated climate implications of ASM are comparable to those of industrial mining.

The investigation also encompassed the collection of primary data for gold production from high-value scrap, which was subsequently evaluated using LCA. The results highlight the particularly low environmental impacts of this production method. This is also of great importance for LCA datasets that try to model a universal gold market, as this route is responsible for approximately 30 % of the annual gold production.

Research in the field of gold from WEEE recycling revealed that the most common process technology, pyrometallurgical recycling, is not sufficiently addressed by LCA studies. It was shown that the high impacts of burning the plastic fraction of the WEEE in the feedstock are responsible for most of the CO_2 equivalents. This leads to a complicated situation for the smelter industry, where efforts for circular economy lead to more impacts on climate change and typical decarbonization strategies fail.

Zusammenfassung

Gold ist seit Jahrtausenden begehrt und wird oft mit Reichtum, Macht und Sicherheit gleichgesetzt. Die Gewinnung von Gold hat jedoch erhebliche Umweltauswirkungen. Dazu gehören ein hoher Ressourcen- und Energieverbrauch, der umfangreiche Einsatz potenziell gefährlicher Chemikalien, wie Cyanid oder Quecksilber, toxische Emissionen sowie die Veränderung der Landnutzung. Die Tatsache, dass Gold der Rohstoff mit der größten Anzahl an Minen ist, macht die ökologischen Auswirkungen besonders relevant.

Zur Untersuchung solcher Umweltauswirkungen eignet sich die Methode der Ökobilanz (life cycle assessment, LCA), die umweltrelevante Stoffströme entlang des gesamten Lebenszyklus von Produkten und Dienstleistungen bewertet und deren Umweltauswirkungen in verschiedenen Kategorien berechnet. In dieser Dissertation werden die wichtigsten Produktionswege für Gold, industrieller Gold- und Kupferbergbau, Kleinbergbau (artisanal and small-scale mining, ASM), Recycling von Altgold und Elektroschrott (waste electrical and electronic equipment, WEEE) mit der LCA-Methode analysiert.

Eine umfangreiche Literaturrecherche ergab, dass Goldproduktion aus ASM und Recycling von Altgold in den gängigen LCA-Datenbanken nicht enthalten sind. Darüber hinaus gibt es erhebliche Datenlücken in Bezug auf den industriellen Bergbau, die häufig durch vereinfachte Extrapolationen, genannt intersystemic data scaling (IDS), geschlossen werden.

In einer methodischen Studie wurde das Problem der Koproduktion in der LCA am Beispiel einer finnischen Kupfermine analysiert. Es wurden verschiedene Allokationsmethoden angewandt und auf ihre Eignung hin diskutiert. Es zeigte sich, dass eine stärkere Fokussierung auf den Nutzen eines Produktsystems anstelle von strengen Hierarchien, die eine Allokationsmethode als generell vorteilhaft gegenüber einer anderen bewerten, sinnvoll wäre.

Um das Fehlen von Daten zu Gold aus ASM in Ökobilanzdatenbanken zu beheben, wurden über 100 Datensätze aus 47 ASM-Minen im brasilianischen Amazonasgebiet erhoben und ausgewertet. Diese Datensätze umfassen den Energiebedarf und die Quecksilberverwendung. Trotz des Einsatzes von Retorten zum Recycling von Quecksilber, wird eine jährliche Freisetzung von etwa 2,5 Tonnen Quecksilber beobachtet. Der Energiebedarf und die daraus resultierenden CO_2 Äquivalente von ASM sind mit denen des industriellen Bergbaus vergleichbar.

Für die vorliegende Dissertation wurden auch Primärdaten für die Goldproduktion aus Altgold erhoben und anschließend mittels LCA bewertet. Die LCA Ergebnisse zeigen, dass diese Produktionsroute nicht nur besonders niedrige Umweltwirkungen aufweist, sondern auch für etwa 30 % der jährlichen Goldproduktion verantwortlich ist. Sie ist daher besonders relevant für LCA-Datensätze, die versuchen einen universellen Goldmarkt zu modellieren (market datasets).

Dagegen wird die gängigste Prozesstechnologie für das Recycling von Gold aus WEEE, das pyrometallurgische Recycling, in Ökobilanzstudien nicht ausreichend diskutiert. Es wurde gezeigt, dass die Verbrennung des Kunststoffanteils im WEEE für den größten Teil der CO_2-Äquivalente verantwortlich ist. Dies führt zu einem Dilemma für die Hüttenindustrie, in dem Bemühungen um eine Kreislaufwirtschaft zu mehr CO_2-Emissionen führen und typische Dekarbonisierungsstrategien scheitern.

Acknowledgements

My research in the field of gold and LCA began in 2018 at the Institute for Industrial Ecology at Pforzheim University under the supervision of Prof. Dr. Mario Schmidt. About two years later, the idea of doing a PhD in this subject formed and was encouraged by him. In 2023, I proposed my idea for a cumulative dissertation at the Institute of Applied Geosciences at Karlsruhe Institute of Technology to my first supervisor, Prof. Dr. Jochen Kolb. My early mentor, Prof. Dr. Mario Schmidt, became my second supervisor and continued to support me throughout this journey.

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List of abbreviations

List of software and databases frequently used.

ecoinvent	LCA database	Wernet et al.(2016)
Sphera (formerly GaBi)	LCA software & database	Sphera Solutions, Inc. (2025)
Umberto	LCA software	iPoint-systems gmbh (2025)
SKARN	Mining database	SKARN Associates (2025)

1. Introduction

On June 8, 1708, the Spanish galleon San José sank in the battle of Barú, carrying immense wealth with loads of gold and silver (Żenkiewicz and Wasilewski 2019). Despite centuries underwater, much of its treasure remains intact. Unlike wood and many metals, which decay over time, gold endures—untarnished and unchanged. This remarkable stability (i.e., inert metal) is one reason why gold has retained its value throughout history, making it a sought-after investment, a key material in electronics, and highly recyclable, but as the example shows, it can get lost.

Past and present alike, humanity is fascinated by gold, as the efforts to find the San José and the decades-long dispute about the rightful ownership of its gold cargo between Colombia, Spain, the indigenous Qhara Qhara people, and a treasure hunting company exemplify (Taylor 2024). However, the narrative surrounding gold is not solely one of allure and value. The extraction and production of gold are associated with numerous environmental and social issues, including high resource demands from mining operations, substantial contributions to climate change, land use conflicts, mercury emissions from artisanal and small-scale mining (ASM), and the financing of illicit activities, among others. Gold is the material with the most mining sites in the world, with more than 17,500 mines, followed by copper with around 8,700 mines (Figure 1, top left), highlighting the relevancy of managing these sustainably (Maus et al. 2022).

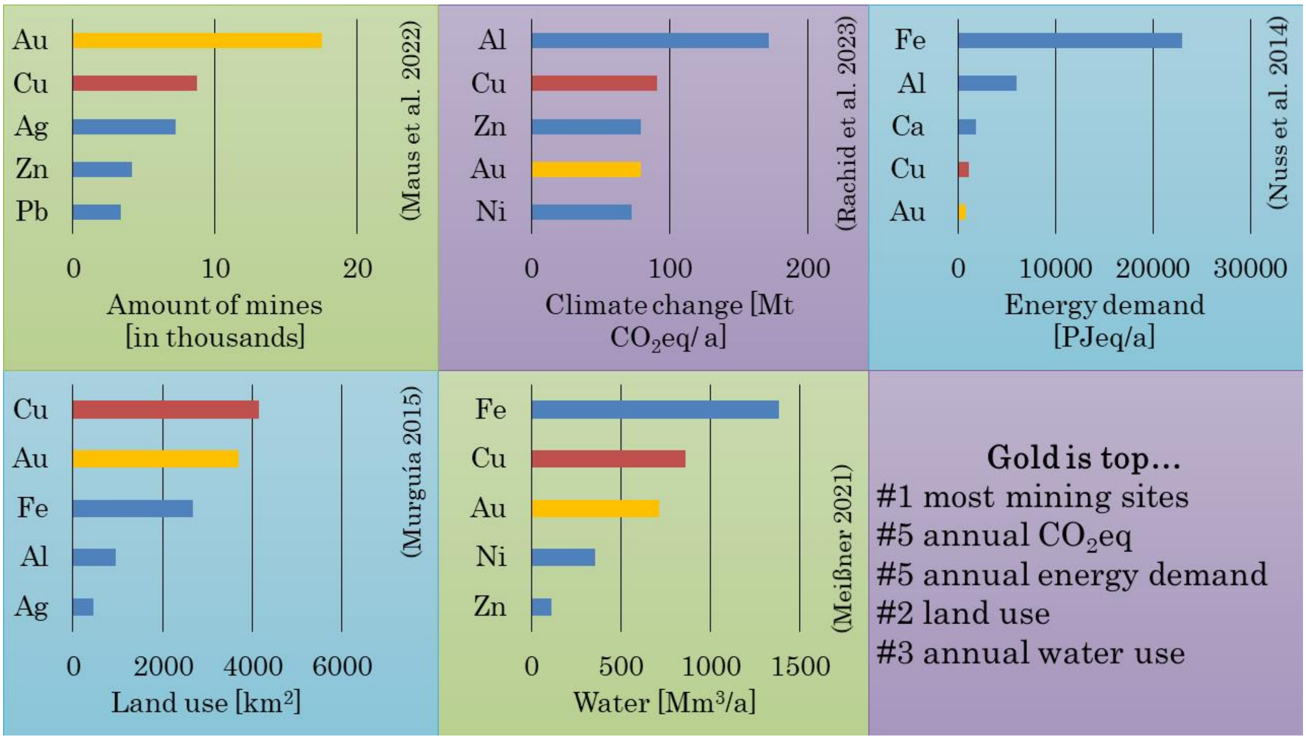

Figure 1: Literature values for annual environmental impacts of gold production (Maus et al. 2022; Meißner 2021; Murguía 2015; Nuss and Eckelman 2014; Rachid, Taha, and Benzaazoua 2023).

Prior to better managing negative environmental impacts, however, knowledge of these must be obtained, i.e., the environmental impacts of gold need to be quantified. One common method to assess environmental issues along the life cycle of products is life cycle assessment (LCA). In brief, LCA is the systematic collection of relevant data along all the life cycle stages of products and services from cradle to grave, followed by the assessment of the environmental impacts caused by them. LCA's holistic approach goes beyond company reports or scientific studies restricted to energy and water consumption, also taking into account the use of, e.g., chemicals, explosives, transports, and direct emissions.

The available LCA studies on gold mining suggest that, e.g., gold has one of the highest carbon footprints of all metals (Nuss and Eckelman 2014; Rachid et al. 2023). Additionally, gold ranks among the top five metals in terms of annual impact on climate change, energy demand, land use, and water consumption (Figure 1). This is noteworthy as gold is produced in relatively small volumes compared to base metals, but its total environmental impacts appear to be in the same order of magnitude as those of base metals such as copper or aluminum (see Figure 1), underlining the significance of reliable LCA data.

However, the problem with LCA studies associated with gold production is that the availability and quality of LCA data for gold production in common LCA databases and in literature are insufficient. Important routes supplying gold to the market in mining and recycling are missing or incomplete. Lacking data points are being filled with vague assumptions, e.g., tailings disposal in gold mining datasets in the LCA database ecoinvent are based mainly on a single company report (Classen et al. 2009:Part IX, 5.1.11; Wernet et al. 2016). Finally, methodological inaccuracies introduce significant uncertainties to LCAs on gold. Figure 2 illustrates a simplified visualization of these issues that are, inter alia, discussed in greater detail in the present thesis.

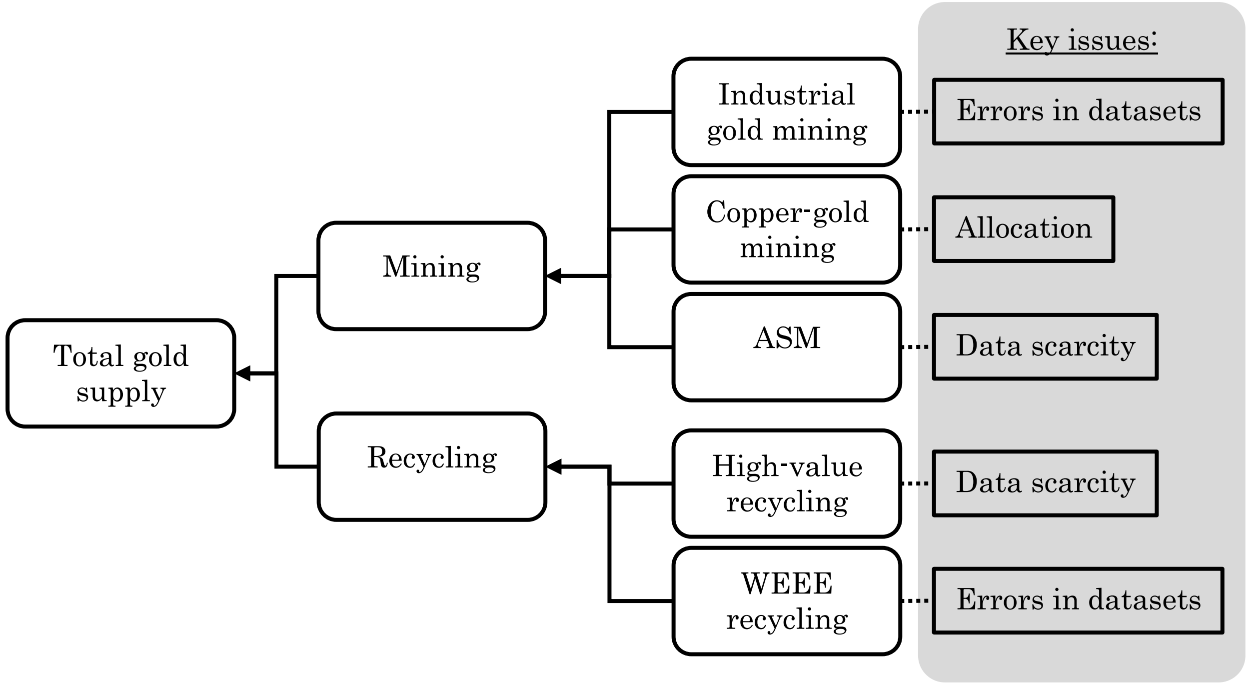

Figure 2: Overview of the main gold production routes and key issues associated with their LCA datasets.

Gold is often produced as a by-product along with other metals, e.g., in copper mining or recycling of waste electronics and electric equipment (WEEE). Gold produced from copper mining amounts to around 10 % of the world's gold supply (Schütte et al. 2023). As a consequence, the question arises of how the environmental impacts of a mine should be allocated between the primary product, e.g., copper, and the by-product gold. In LCA, this issue represents a central methodological question that has been debated in LCA communities a long time and has significant effects on LCA results for gold (Lai et al. 2021; Santero and Hendry 2016; Schrijvers, Loubet, and Sonnemann 2016).

When it comes to sustainability, one particularly critical route is the gold production from ASM. It is estimated that around 18 million miners extract gold in ASM around the globe (Hruschka 2023). There are many studies on ASM in different scholars like anthropology, toxicology, geology, or engineering (Hentschel, Hruschka, and Priester 2002; Hilson and McQuilken 2014; Hinton, Veiga, and Veiga 2003; Ofosu et al. 2020). Especially the problem of mercury has been widely discussed in academia, news, and by NGOs. Mercury is a highly toxic element that poses significant risks to human health, particularly affecting neurological, immune, and developmental functions, and is therefore recognized by the WHO as a major public health concern (World Health Organisation 2024). One strategy to cope with mercury emissions proposed in ASM around different countries is the use of retorts to recycle parts of the mercury instead of emitting it to the environment. Notwithstanding the relevancy of ASM, this route is missing in common LCA databases. Some essential open questions are how much mercury and energy are being used, what quantitative benefits do retorts have, and whether the resource intensity of ASM is lower than in industrial mining.

Apart from the mining of gold, another relevant source needs to be assessed when attempting to understand the LCA of gold. Given gold's high value and chemical stability, a large quantity of gold is sourced through recycling processes. Some even call it a blueprint for recycling, as almost no gold (≈5 %) has ever been lost (Butterman and Amey 2005). However, the environmental impacts associated with recycling gold have not been sufficiently quantified. There is no LCA study on producing gold from high-value materials like old jewelry or goldsmith's sweepings, although this route is responsible for 90 % of the gold production from recycling (Hewitt et al. 2015). Because the most common production process for this is using hydrometallurgy, i.e., aqua regia, the holistic approach of LCA is suggesting itself for assessing its environmental impacts and identifying possible areas for improvements.

A small portion of the gold supply is used for technology, i.e., mainly for non-corrosive electrical contacts because of gold's noble characteristics. Although the size and weight of the electronics are decreasing, the total production and thus waste volumes are rising (Baldé, Kuehr, and Yamamoto 2024). WEEE poses significant risks for people and the environment if not properly recycled. Hence, recycling gold from WEEE could be a win-win situation, lowering the environmental impacts from mining and from improper WEEE management. However, recycling WEEE is not without environmental impacts. The most common route for recycling gold from WEEE is pyrometallurgical recycling by using the copper smelter infrastructure. LCA data for this route is scarce and contains errors. The fact that the pyrometallurgical process uses the fossil carbon content in the plastic fraction of the WEEE as an energy source and reduction agent might lead to challenges for sustainable circular economy (CE) strategies.

In this work, a first analysis of the current state-of-the-art LCA datasets for gold revealed that data for ASM and for recycling of high-value scraps are missing completely and data for industrial mining contain uncertain assumptions (Paper I). Gold is often produced as a by-product in the mining of multi-metal ores or the recycling of scraps. The question of how to allocate LCA results between gold and other by-products when produced jointly, e.g., in copper-gold mining, has a significant effect on the end results of the LCAs and is hence being discussed (Paper II). Research about the missing route of ASM was conducted in several expeditions to the Brazilian Amazon rainforest, where more than 100 data points of on-site data about energy and diesel use in ASM were gathered (Paper III). For the other missing route, high-value recycling, the present dissertation provides detailed LCA analyses (Papers IV and V). Finally, errors in the datasets for gold from WEEE recycling led to investigating the most common process for this route in more detail (Paper VI). The questions that this cumulative dissertation tries to answer by each of these contributions are visualized in Figure 3.

Chapter 8 **Analysis of Life Cycle Datasets for the Material Gold** Check for updates Benjamin Fritz and Mario Schmidt **Paper I**	• How accurate is the representation of gold in the most common LCA databases? • How much gold is produced through the main production routes?
PAPER Gold from copper mining as a case study for allocation in life cycle assessment Benjamin Fritz[1] and Mario Schmidt[2,*] [1] Institute for Applied Geosciences (AGW), Karlsruhe Institute of Technology (KIT) [2] Institute for Industrial Ecology (INEC), Pforzheim University [*] Author to whom any correspondence should be addressed. **Paper II**	• How suitable are different allocation methods in LCA for gold production as a by-product of base metals? • What role do changes in the price of gold and copper play for economic allocation?
nature sustainability Article https://doi.org/10.1038/s41893-023-0 **Mercury and CO_2 emissions from artisanal gold mining in Brazilian Amazon rainforest** Received: 22 March 2023 Accepted: 4 October 2023 Benjamin Fritz[1], Bernhard Peregovich[2], Lorena da Silva Tenório[2], Adria Cristina da Silva Alves[2] & Mario Schmidt[1] **Paper III**	• How much mercury is used, recovered, and lost in ASM? • What is the energy demand for gold from ASM? • Is the carbon footprint of ASM lower than that of industrial gold mining? • How do the processes involved in transporting goods to and from the ASM operations in the jungle affect the LCA results?
The International Journal of Life Cycle Assessment (2020) 25:1930–1941 https://doi.org/10.1007/s11367-020-01809-6 DATA AVAILABILITY/DATA QUALITY **Environmental impact of high-value gold scrap recycling** Benjamin Fritz[1] · Carin Aichele[1] · Mario Schmidt[1,2] **Paper IV**	• What are the environmental impacts of gold production from high-value scrap using LCA's holistic approach? • Which allocation method should be applied for the LCA of high-value gold recycling?
Benjamin Fritz et al.: An Ecological Analysis of the State-of-the-Art Refinery of High-Value Gold Scraps **An Ecological Analysis of the State-of-the-Art Refinery of High-Value Gold Scraps** Benjamin Fritz, Mario Schmidt **Paper V**	• How can the environmental impacts of gold production from high-value scrap be further improved? • How do the processes involved in transporting gold bearing products to and from the recycling plants affect the LCA results?
sustainability MDPI *Article* **Climate Change vs. Circular Economy: Challenges of the Most Common Route for Recycling Gold from WEEE** Benjamin Fritz[1] and Mario Schmidt[2,*] [1] Institute of Applied Geosciences, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany [2] Institute for Industrial Ecology, Pforzheim University, 75175 Pforzheim, Germany [*] Correspondence: mario.schmidt@hs-pforzheim.de; Tel.: +49-7231-28-6406 **Paper VI**	• How does the plastic fraction of WEEE challenge typical decarbonization strategies for copper smelters recovering gold from WEEE? • What decarbonization options exist for recycling processes where fossil carbon is embedded in the input material? • How do transport processes affect the LCA results for gold recovery from WEEE?

Figure 3: Research questions addressed in this dissertation.

2. Overview of gold

2.1. Technological properties of gold

Gold is in the 11th group in the periodic table of elements and is the 79th element. Together with copper and silver, this group is referred to as coinage metals. Gold occurs in nature in its pure form. It fulfills all the arbitrary distinctions of precious metals: resistance to air, moisture, and normal wear. It is amongst the elements with the highest density, with around 19.32 g/cm^3 at Standard Ambient Temperature and Pressure (SATP). This is why a typical gold bar, which is ≈25 cm long and ≈5 cm wide and high (well-known from heist movies), is surprisingly heavy (≈400 oz ≈12 kg). The melting point for gold is around 1064°C SATP. Mercury, on the other hand, evaporates at a lower temperature (356.7°C SATP) and easily forms an alloy with gold (amalgam). This enables the simple separation of gold from mercury with heat, a process still employed in ASM (see Paper III). The conductivity of gold is 4.1×10^7 S/m, which is around 2 S/m lower than copper (Renner et al. 2012). It is the most ductile of all metals and can be beaten into gold foil with a thickness of 100 nanometers (Rösner et al. 2007). Gold is not reacting with most of the chemicals that naturally affect many other metals, like water, oxygen, or ozone, inter alia, making it a desired material in jewelry and technology. There are only very few chemicals that do affect gold, such as aqua regia (a mixture of HNO_3 and HCl), cyanide, and chlorine. Gold forms alloys with many metals. Important ones are zinc, which can be used in cyanidation, and the aforementioned mercury, which was traditionally used in gold mining and is nowadays only used in ASM (Renner et al. 2012). More details on cyanidation, amalgamation, and aqua regia can be found in section 2.2.

Besides gold's role in jewelry and investment, it also has technical applications, especially due to its inert character, its rather high conductivity, and its ductility. It is therefore frequently used in electronics where long-lasting, non-corrosive contacts are required. Gold is also used in very small electronic parts as nanosized gold particles. The gold used in electronics, besides solders, has high purity. The usage of gold in electronics, as well as the rising sales of electronics, increases the potential of urban mining through WEEE. Given the high resource intensity of gold mining, LCA studies on electronics have already identified gold as a significant contributor to product environmental footprint, emphasizing the importance of more comprehensive and reliable LCA data on gold (Ercan et al. 2016; O'Connell and Stutz 2010). Besides electronics, gold is also used in medicine as gold colloids, which are liquids with nanoparticles of gold (Renner et al. 2012). One popular known application is the COVID-19 rapid tests, where the gold colloids are responsible for visualizing the result with a red line (Ardekani and Thulstrup 2022). The ductility and the shiny yellow color lead to the usage of gold for technical and decorative coatings.

Common processes are electroplating, gold paint, and leaf gold (Renner et al. 2012). Gold plating is used in aerospace and satellite technology, e.g., the mirrors of the James Webb Telescope. Plating the entire 25 m^2 area of this telescope only needed ≈48 grams of gold (Siegel 2017). According to Giurlani et al. (2024), sustainability is an important concern of the plating industry, further highlighting the relevance of comprehensive LCA datasets for gold.

2.2. *Gold production*

Table 1 shows the major process routes used to produce gold based on their raw material input, including common process technologies used.

Table 1: Gold production routes by raw material input and common processing technologies.

Production route	**Raw material**	**Common process**
Industrial gold mining	Ore with high gold content	Cyanidation
Copper-gold mining	Copper ore with gold as by-product	Pyrometallurgy
ASM	Secondary deposits and ores	Amalgamation
High-value recycling	High-value gold scraps	Aqua regia
WEEE recycling	WEEE	Pyrometallurgy

The gold supply chain is characterized by a lack of transparency since there is no comprehensive compilation of market shares for these routes, which are essential for "market datasets" in LCA databases. Market datasets try to model the market situation for a specific product and region, including different production routes and logistics. They are frequently used for material flows, where very little specific information about their origin is known. This emphasizes the need for more transparency in the gold industry involving policymakers as well as mines, refineries, recycling plants, banks, and gold shops. The production routes shown in Table 1 are described in more detail in the following two sections on mining and recycling.

2.2.1. Mining

Primary deposits are gold enrichments in the crust that form in a broad range of pressure and temperature (Hector 2023). They are formed "by processes involving magmas (i.e., molten rock) and hydrothermal fluids (literally hot waters that are in the Earth's crust)" (Phillips 2022:5). Primary deposits can be mined above and below ground. Surface mining is currently on the rise in industrial gold mining, as it is easier, cheaper, and faster to develop the mine (Norgate and Haque 2012). Today, industrial gold mining mainly uses cyanidation for gold extraction from the ore (Adams 2016:xi; Norgate and Haque 2012). Around one billion tons of ore are leached with cyanide every year (Adams 2016:11).

The leaching of gold in cyanide is an electrochemical process in which oxygen absorbs electrons from the gold surface, while gold ions enter the solution and are quickly complexed by cyanide ions. If zinc dust is used to precipitate gold, this is known as the Merrill-Crowe process. As an alternative to precipitation with zinc, activated carbon can also be used. This enriches the leached gold. The technical term used for this is "gold-laden carbon". In the past, the activated carbon was then burned and remained as ash, while the gold could be poured into bars. However, this process was too complex and expensive compared to the Merrill-Crowe process. Subsequent to this, the carbon-in-pulp or carbon-in-leach process led to a renewed utilization of activated carbon. In this process, gold and silver were extracted from the activated carbon by electrolysis without incinerating the coal (Adams 2016:15f). Different ores are suitable for different processing technologies. One particular technology that accounted for 15 % of industrial gold mining in 2011, mainly used for low-grade deposits with high-tonnage, such as copper porphyry, is heap leaching (Adams 2016:27). In this process, plastic sheeting is laid on the ground, and the crushed ore is piled up in heaps on top of it with hoses fitted around the heaps. The cyanide then drips from these hoses onto the ore over several months and dissolves the gold. At the end, the solution with the enriched metals (pregnant solution) is pumped into a processing plant to extract the gold (Bleiwas 2012).

Cyanidation can be hazardous to human health and the environment when used improperly. In the past, accidents have been reported with tremendous consequences (ICMI 2020). Such as the Baia Mare cyanide spill in January 2000 in Romania, which contaminated transboundary rivers and caused extensive ecological damage and water supply contamination. One particular usage of cyanidation can be found in ASM, where it is used after amalgamation to extract any remaining gold. This practice is considered especially problematic by the Minamata Convention, a UN resolution ratified by 148 countries in 2013 to cope with mercury emissions. This is because mercury-cyanide compounds can be formed, which are extremely toxic for humans and the environment (UNEP 2013). Due to these concerns, alternatives are being sought. Thiourea and thiosulphates appear to be technically good alternatives with the same or better leaching properties for gold, but they are less economical (Norgate and Haque 2012).

Secondary deposits are the result of alteration or weathering (Renner et al. 2012). They are mainly mined by dredging from watercourses or by washing old riverbeds with hoses, sometimes called hydraulic mining (McQueen 2005; Priester, Hentschel, and Benthin 1993). They can be subdivided into eluvial, alluvial, and colluvial. Eluvial deposits are weathered deposits that are still close to their primary deposit, while colluvial deposits are transported by gravity, for example, on scree slopes (Miller and Juilleret 2020). In alluvial deposits, the gold is transported by rivers and deposited along them, depending on flow velocities and currents. Because they can be mined by simple and well-known methods and are, due to their complex geometry, less attractive to industrial mining, they are often processed by ASM (Tarra, Restrepo, and Veiga 2022). Probably the most common method in ASM is a combination of gravity separation and amalgamation, where mercury's ability to form alloys (amalgams) is used. Gold and other metallic particles are attracted to bond with mercury and form an amalgam. This makes it easier to separate even fine gold particles from crushed ore or sand, e.g., by panning. After separation, surplus mercury is removed from the amalgam by a filter press. A common, rudimentary method for this in ASM is twisting the amalgam in a piece of fabric. Next, the mercury is removed from the amalgam by heating, causing it to evaporate. To lower hazards associated with this process and to recycle the mercury, a retort can be used to distill the mercury vapors (Priester et al. 1993; Veiga et al. 2006).

Besides primary and secondary deposits, gold ores can also be distinguished from one another as refractory and non-refractory gold ores. The term "refractory" comes from Latin and means "inaccessible" or "resistant"; in the context of gold mining, it refers to ore in which the gold content is difficult to access (Fraser, Walton, and Wells 1991). Differences in processing of refractory ores compared to non-refractory ores, such as additional roasting steps, tend to slightly raise their environmental impacts (Norgate and Haque 2012).

Gold as a by-product from the mining of other metals like copper is another important production route. Gold from copper mainly stems from copper sulfide ores, which are mostly treated pyrometallurgically in copper smelters (Adams 2016:803). The gold remains in the anode slime after producing the cathode copper. One typical process scheme for extracting the gold from the anode slime is to first separate the silver using a Moebius electrolysis and then extract the gold using a Wohlwill electrolysis. Often platinum group metals (PGM) are extracted from the residue using hydrometallurgical processes (Moosavi-Khoonsari and Tripathi 2024). The by-products in the copper concentrates often significantly contribute to the revenue of the smelters (Aurubis AG 2024; Chen and Dutrizac 2008).

Gold refining of newly mined gold, called doré, is typically performed by refiners that are not owned and operated by the mining sites. The gold content of the doré varies between 30 % and 98 %, with the difference mainly made up by silver. The exact composition containing other elements like zinc, selenium, or mercury varies largely between different locations and mining sites. The most common process to refine gold doré is Miller chlorination with subsequent Wohlwill electrolysis. The gold is first melted while injecting chlorine gas. This process separates many impurities from the gold as chlorides, such as silver chloride, are formed. The pre-refined gold is then upgraded to 99.9 % purity using Wohlwill electrolysis, as already mentioned in the section above on gold as a by-product (Adams 2016:599f; Auerswald and Radcliffe 2005).

2.2.2. Recycling

High-value gold recycling is the recycling of, e.g., old jewelry, coins, or goldsmith's sweepings and accounts for ≈90 % of the gold recycling (Hewitt et al. 2015). One of the most important processes for recycling high-value gold material is the aqua regia process. Aqua regia is the 3:1 mixture of concentrated hydrochloric and nitric acid. Impure material with high gold content can be dissolved in aqua regia (Adams 2016:599f). Silver forms an insoluble silver chloride in aqua regia that is typically filtered off (Yannopoulos 1991:244). If the silver content in the input material is higher than around 15 % (e.g., in doré), the gold dissolution is negatively affected (Adams 2016:604). After the silver is removed, the gold can be precipitated from the solution, e.g., by sulfur dioxide. PGMs can be further extracted from the residue by hydrometallurgical processes (Adams 2016:599; Yannopoulos 1991:244). Some refineries mix doré material with recycling material to achieve a feedstock suitable for aqua regia. Although the processes in refining and recycling are somewhat similar, refineries and recycling plants can be distinguished by the type of feedstock, i.e., accepting newly mined material (see section 2.2.1). Another source of input for high-value recycling, although low in its initial gold content, is goldsmith's sweepings. This input material typically has high organic carbon content, which is incinerated prior to the aqua regia process (Corti 2002).

WEEE recycling for producing gold is responsible for the significantly smaller part of the gold production from recycling (≈10 %). WEEE recycling can be distinguished between formal and informal recycling. The most common process in formal WEEE recycling is to mix the WEEE with ore concentrates in copper smelters. The plastic content of the WEEE is typically used as an energy carrier and reduction agent within the pyrometallurgical process (Hagelüken 2006). The gold is then extracted from the anode slimes electrometallurgically, e.g., using Moebius followed by Wohlwill electrolysis. This is similar to the aforementioned gold extraction as by-products from copper concentrates (see section 2.2.1). Remaining PGMs are further refined from the residue using hydrometallurgical processes. Less is known about the gold production from informal WEEE recycling. It is assumed that some of the gold-bearing material from informal WEEE recycling sites in the Global South, like Accra market in Agbogbloshie, Ghana, is sold to recycling facilities in the Global North for gold production (Baldé et al. 2024; Illes, Geeraerts, and Schweizer 2015; Owusu-Sekyere et al. 2022). There is little evidence that some gold is also produced directly in informal WEEE recycling, which shows similarities in technology and social structure to ASM (Keller 2006; Moyo et al. 2022).

2.3. Market for gold

In 2024 the biggest share of the gold demand was used for investment and central banks, with 2,200 t (≈49 %) as can be seen in Figure 4, showing the gold demand by its three main purposes.

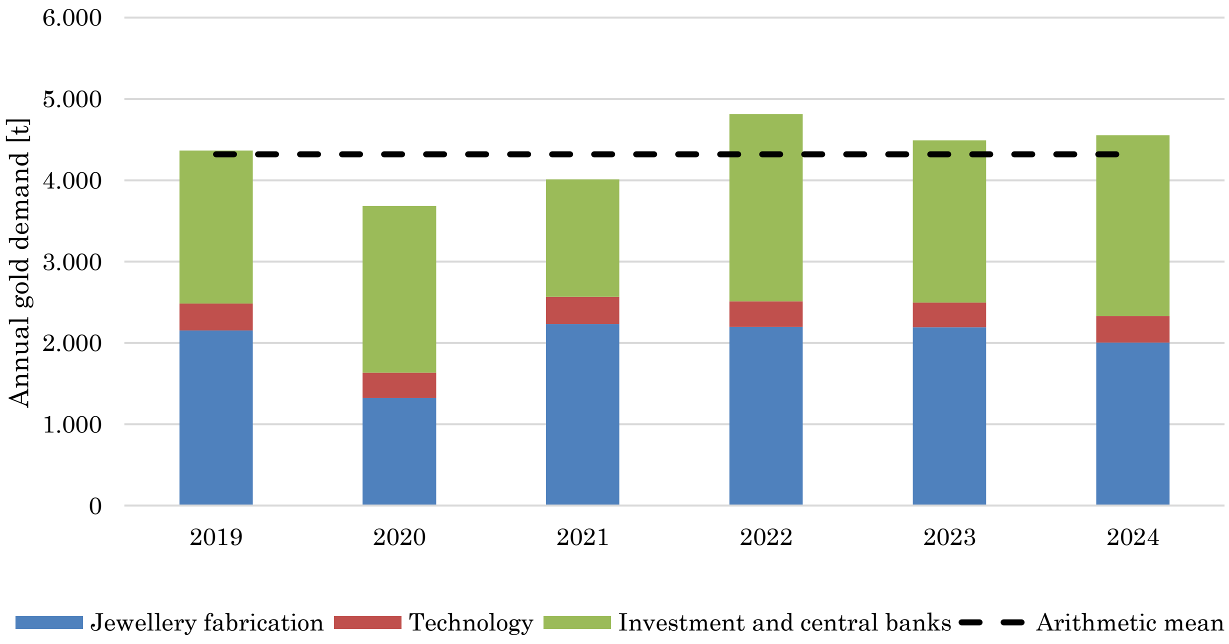

Figure 4: Gold demand by sector based on World Gold Council (WGC) between 2019 and 2024 (WGC 2025a).

This is followed by around 2,000 t (≈44 %) for use in jewelry. The remaining around 330 t (≈7 %) are used for technological purposes, i.e., mainly the electronic industry. The mean production between 2019 and 2024 was ≈4,300 tons (see dotted line in Figure 4). The total annual demand fluctuated by ≈20 % between 2010 and 2024 (≈10 % when excluding the COVID-19 pandemic years), while the gold price has fluctuated by ≈50 % (see Figure 5).

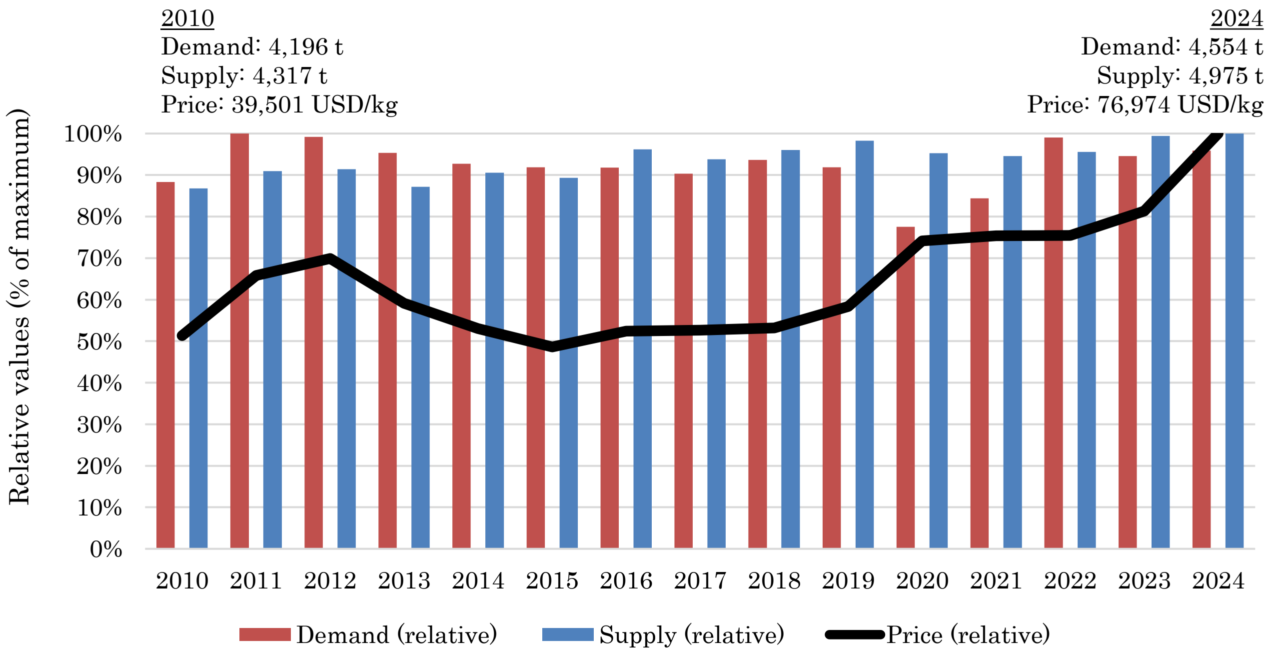

Figure 5: Relative gold price, demand and supply between 2010 and 2024 based on WGC (2025a). Normalized to category maxima (% of maximum).

The total annual gold supply between 2019 and 2024 was around 4,800 t (see dotted line in Figure 6).

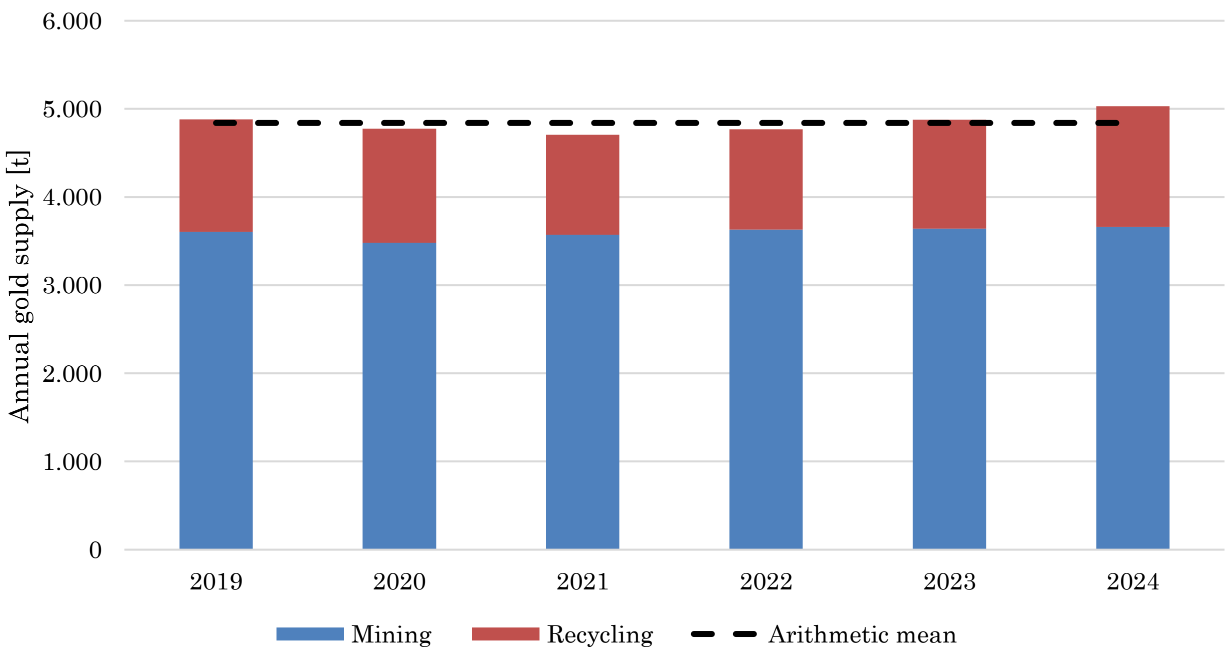

Figure 6: Gold supply from mining and recycling between 2019 and 2024 based on WGC (2025a).

As shown in Figure 6, the supply is predominantly satisfied by newly mined sources, accounting for approximately 70 % between 2019 and 2024. Especially gold mining is well-known for its high resource intensity, indicating the need to understand and improve LCA data for this route.

Around 30 % (2019-2024) of the world's gold is sourced from recycling, of which about 90 % originates from high-value recycling, while the remaining 10 % is derived from WEEE (Hewitt et al. 2015). Examples of high-value scraps are jewelry and goldsmith's sweepings. Particularly WEEE is often discussed in the context of CE strategies and tends to be slightly overrepresented in public and scientific debates, considering its relatively low supply. The supply of gold from high-value recycling on the other side appears to be of less focus in recent debates but might offer a more sustainable gold production from recycling than WEEE and is available in larger quantities (see Figure 6). The total annual supply was fluctuating ≈10 % between 2010 and 2024, although the gold price has fluctuated by ≈50 % (see Figure 5).

It is imperative to acknowledge the challenges associated with the collection of these figures. Some gold is traded for purposes such as corruption and money laundering, occurring outside the formal economic structures of official markets. Additionally, the gold industry has historically maintained a high level of confidentiality with regard to the disclosure of production figures (Gomez 2024; Mbiyavanga 2019). Moreover, the gold produced in ASM is hard to track and thus hard to include sufficiently in statistics (Manzolli et al. 2021).

Large quantities of gold are traded within the London Bullion Market Association (LBMA). The gold traded here is supposed to meet certain responsibility standards, and the LBMA does collect and publish data on their gold suppliers and volumes traded. In the latest LBMA report, it is stated that 3,400 tons were sourced from recycling, 1,900 from industrial mining, and 51 from ASM in the reference year 2022 (LBMA 2024). This adds up to ≈500 tons more than the total gold supply reported by the WGC for the same year (WGC 2025a). Another interesting difference when comparing the WGC and the LBMA values is the large amount of gold from recycling reported by the LBMA. This probably stems from methodological limitations by the LBMA, i.e., inconsistent definitions of recycling and data inconsistencies due to manual data entry (LBMA 2024). This example of vague public data on gold production and trade highlights the need for more transparency in the gold industry.

Figure 7 shows the 2023 production by the top 13 gold-producing countries. Where available, corresponding gold recycling quantities (red bars) are also shown alongside mining figures (blue bars). Recycling data were included only for countries for which explicit values were reported in Newman et al. (2024b).

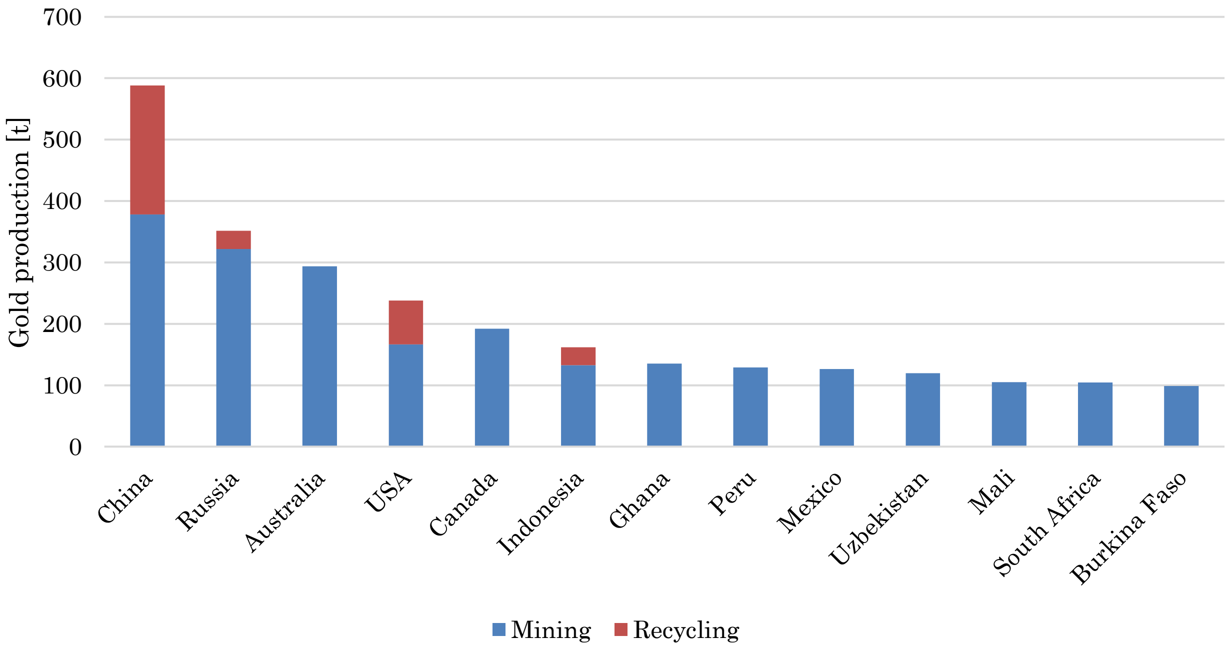

Figure 7: Gold production by the top-producing countries in 2023 (Newman et al. 2024b).

The chart shows that China is the country with the highest gold production. This has not always been the case. According to Grewe (2019:121), China only moved ahead of South Africa in 2007. Now it produces more than the USA and Canada combined (see Figure 7). This also significantly contributes to the problem of data availability, as data from China, in particular, is often not available (Ulrich, Trench, and Hagemann 2022). Some studies indicate that gold mining in China tends to have higher LCA results compared to the industry average, highlighting a present relevancy of the topic (Chen et al. 2018). This raises the question of whether such regional differences are accurately represented in common LCA databases for the material gold.

Gold remains largely available in the system due to its economic and ideological value as well as its physical and chemical properties. This is different from other mined commodities such as coal or base metals, which are subject to high dissipation or even chemical transformation. Figure 8 visualizes all the gold that has ever been mined cumulatively (≈216,000 tons) in a cube using the density of gold. This cube would have an edge length of just ≈22 m, and ≈2/3 of it was mined after 1950 (WGC 2025b).

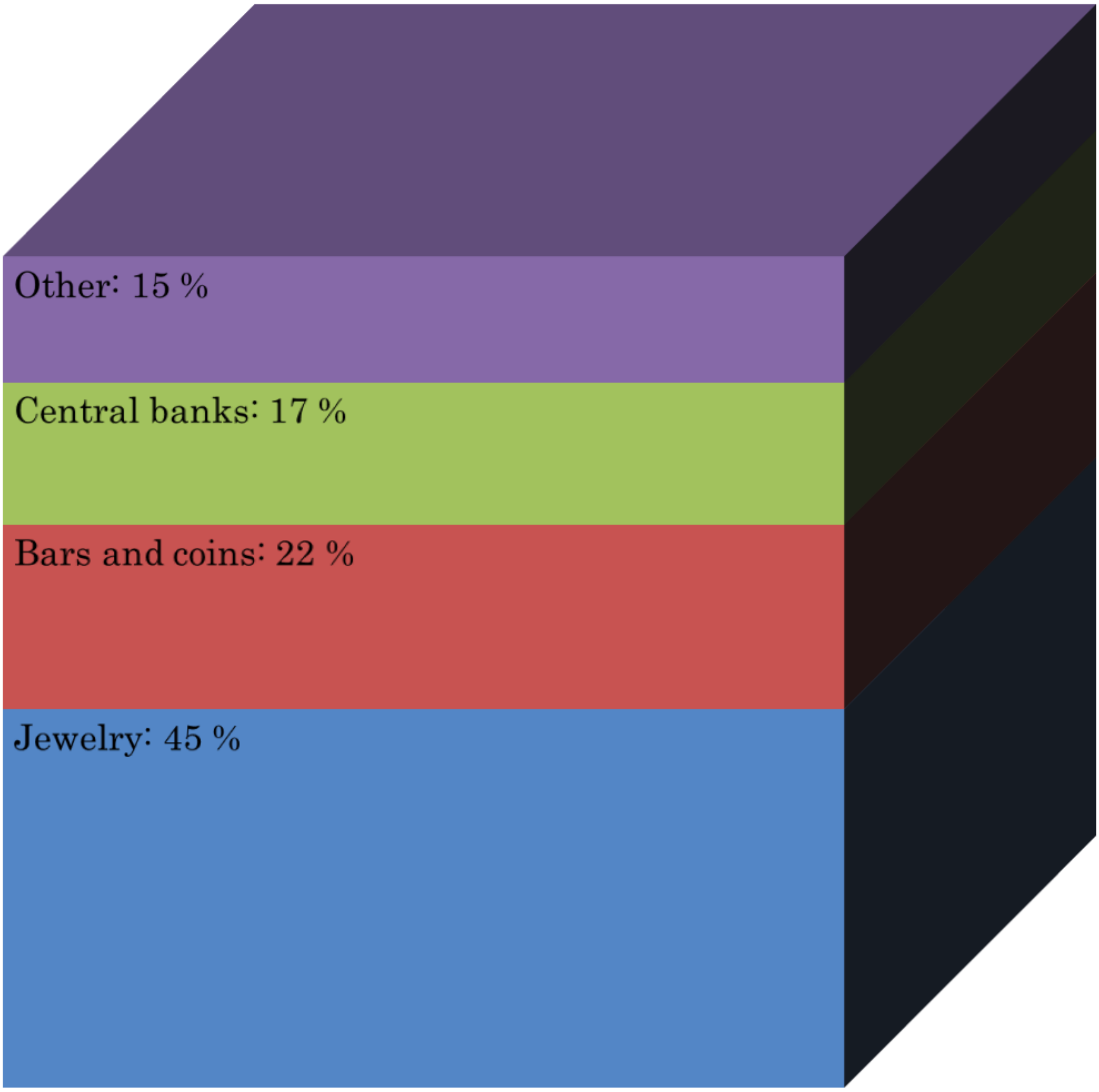

Figure 8: Visualization of the total volume of gold ever mined (≈216,000 t) and its distribution among different stock types (WGC 2025b).

If gold stocks from banks and vaults were used to meet the gold demand for jewelry and industrial goods (arithmetic mean for 2019 to 2024, see Figure 4), no gold mining would be necessary for more than 30 years. This thought experiment has recently led Lezak et al. (2023) to question whether a moratorium on gold mining should be declared. The researchers draw parallels with turning away from ivory or coal for social and environmental reasons, which are also topics concerning gold mining. It may be assumed that, unlike ivory or coal, gold can less easily be substituted due to its unique combination of roles as a monetary asset, industrial material, cultural symbol, and status indicator.

3. Life cycle assessment (LCA)

3.1. Overview

LCA is a method for assessing the environmental impact that certain products or services can have. It dates back to the early 1970s, when Coca-Cola examined the environmental impact of various beverage packaging (Hunt, Franklin, and Hunt 1996). As the word "life cycle" suggests, the environmental impact over the entire life cycle of a product is assessed. Figure 9 shows common life cycle stages of a product.

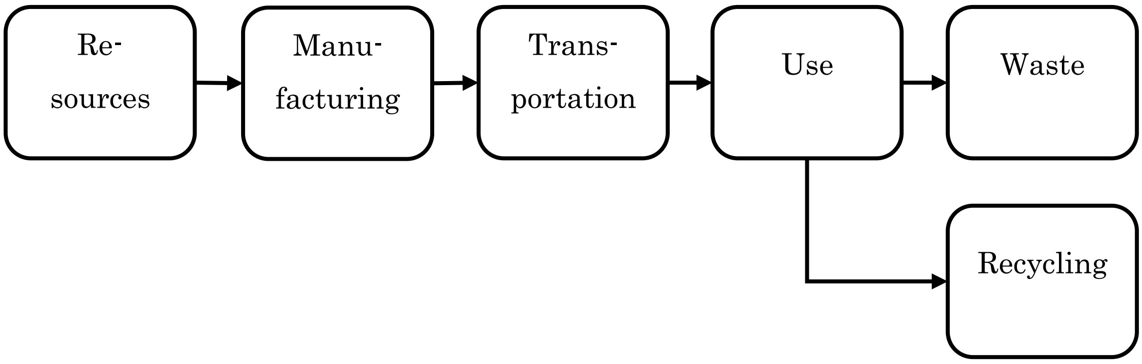

Figure 9: Common life cycle stages of a product.

As most of the gold is recycled, for its life cycle a particularity exists, since there is almost no waste disposal phase.

Since 1997, there have been two comprehensive standards, ISO 14040 and ISO 14044, on life cycle assessment (International Organization for Standardization 2020a, 2020b). Figure 10 shows the four phases of life cycle assessment according to ISO 14040 standards.

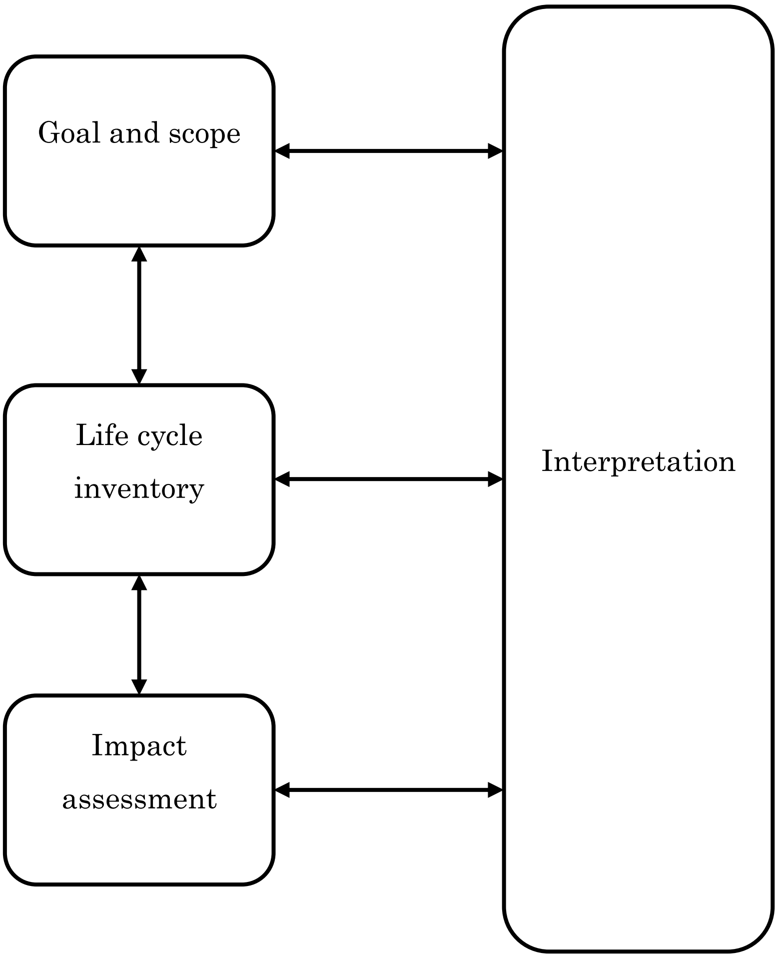

Figure 10: Four phases of an LCA according to ISO 14040 (International Organization for Standardization 2020a).

In the remainder of this section, as well as in the next section on allocation (section 3.2), it is intended to explain the various phases of LCA in a simplified manner, using gold as an example (where possible), and to supplement this with some practical experience.

To compare the environmental impacts of two identical gold rings, one made with gold mined in China and another with gold from a recycling plant in Germany, LCA is a suitable method. The first step in LCA is the goal and scope (see Figure 10), where the system is defined. One important part of this is defining a functional unit, which in this case could be a 14 carat gold ring (≈60 % gold by mass) weighing 5 g and therefore containing about 3 g of gold. The system boundary could be the respective production of the gold in the mine or the recycling plant up to the shop window of a goldsmith.

Next, the relevant impact categories in the LCA need to be selected. Impact categories describe how the inputs and outputs of a product system—such as methane emissions—affect the environment. This is often explained as a cause-effect chain, where the emission (e.g., methane) is the cause and the environmental impact (e.g., climate change) is the effect. Impact categories are usually divided into mid- and endpoints. Midpoints are closer to the cause in the chain, while endpoints are closer to the effect (Bare et al. 2000). For example, methane emissions contribute to climate change, which can be measured at the midpoint level in CO_2eq. This effect on climate change can then attribute to the endpoint of human health, which is measured at the endpoint level in disability-adjusted life years (DALY). In the case of the gold ring, the LCA might focus on midpoint categories such as land use or human toxicity. However, many different impact categories exist, and selecting the most appropriate ones can be a complex task. There have been several attempts in LCA to find single-score indicators condensing many of the environmental impacts into one number. However, this approach has been criticized because of the large amount of weighting and aggregation and thus subjective choices (Kalbar et al. 2017). Some papers within this dissertation are only analyzing impacts on climate change and can therefore be considered a carbon footprint (ISO 14067) instead of an LCA (International Organization for Standardization 2018). Carbon footprints are often referred to as the little sibling of the LCA (DEKRA 2023). There are several reasons for focusing on this specific impact category. In particular, climate change is frequently referred to as one of the most pressing challenges of our time. The topic is well known around the globe, and the impacts of climate change not only affect surrounding areas but the whole planet. Additionally, the impact category is quite elaborate, well standardized, and comprehensive. According to Rosenbaum (2018), impact on climate change is regarded as fairly certain, while, e.g., impact on human toxicity is not. Lastly, some of the literature suggests that many impact categories strongly correlate with CO_2eq (Pascual-González et al. 2016; Steinmann et al. 2016).

The next step in LCA is to research the in- and output flows for the various processes throughout the life cycle. For example, how much cyanide or explosives are used by the mine in China, and how much aqua regia is needed by the German recycling plant to produce one kilogram of gold? Flows like these are called technosphere flows because they have already gone through production processes, and the initial extraction of natural raw materials has happened before (Hofstetter 1998:33f). The flows that are taken directly from or are emitted to nature, e.g., the rock in the ground or chemicals emitted to air when refining, are called biosphere flows. This information forms the basis for the life cycle inventory (LCI, see Figure 10), also referred to as foreground LCI (Frischknecht 2020:247). But the cyanide input for this exemplary foreground LCI has its own LCI table. Meaning that the production of cyanide requires methane and ammonia, which, in turn, have a corresponding LCI, and so forth. (Frischknecht 2020:33). This is called background LCI. As it would be extremely time-consuming to research every production process for all auxiliary and operating materials, LCA databases are used. These databases contain common materials or services for various locations, such as the production of cyanide in the USA. The two most widely used databases are the proprietary databases Sphera (formerly GaBi) and ecoinvent (Martínez-Rocamora, Solís-Guzmán, and Marrero 2016). In these databases, all datasets have been researched and analyzed until they have a biosphere flow, such as emissions from a chimney or toxic substances released into the soil. Consequently, LCA presents an advantage when compared to methods like energy assessments, as it allows for a holistic view of a product system, including the environmental impacts of auxiliary materials.

After the LCI phase, the next step is the modeling of the two product systems—gold from the mine and gold from the recycling plant—based on their LCI. Software tools are generally used for this, whereby well-known paid applications such as SimaPro (PRé Sustainability B.V. 2025), Sphera (formerly GaBi), Umberto and open-source tools such as OpenLCA (GreenDelta GmbH 2025) or Brightway (Mutel 2017) are used. In the present work, mainly Umberto, due to its ease in modelling, and Brightway, because of the powerful analysis options, were used. These tools enable step-by-step modeling of the life cycle of the exemplary ring for each process step. This is also referred to as the foreground system. The software helps to search and match the relevant LCI entries from the foreground with the technosphere flows from the database. By matching the foreground LCI with the technosphere flows from the database, the background LCI is created. Due to the biosphere information on the technosphere flows in the database, this generates a complete background LCI, which includes all associated biosphere flows.

The mathematical backbone of LCA uses matrix operations. The technosphere part of the LCI table is called technology matrix A, and the biosphere part is called intervention matrix B. The whole LCI table in matrix form is called process matrix P (Heijungs and Suh 2002:14).

The software assigns the biosphere flows to their specific impacts on the environment using impact assessment methods. For example, the emission of 1 kg of methane has about 30 times the effect on climate change as 1 kg of CO_2 and, therefore, about 30 kg CO_2equivalents (eq). In the matrix calculations this corresponds with the characterization matrix Q (Heijungs and Suh 2002:168).

After specifying the reference flow f in the software, the impact assessment (see Figure 10) can be computed. The mathematical backbone for this is to use the technology matrix A to find the scaling vector s by using Equation 1.

Equation 1: Scaling vector according to Heijungs & Suh (2002:17).

$$s = A^{-1}f$$

Next, s and the biosphere matrix B are used to calculate the inventory vector g as shown in Equation 2.

Equation 2: Inventory vector according to Heijungs & Suh (2002:18).

$$g = Bs.$$

To compute the impact vector h, one has to multiply g with the characterization matrix Q, as can be seen in Equation 3.

Equation 3: Impact vector according to Heijungs & Suh (2002:18).

$$h = Qg.$$

After running the calculations in the software, according to ISO 14040, the last step of an LCA, called interpretation (see Figure 10), demands critically analyzing the results (International Organization for Standardization 2020a). Some typical questions in this step could be, "Which auxiliary and operating materials contribute most to the LCA results?"; "Which foreground processes do significantly affect the results?"; "Is this plausible?"; "Which sometimes serious environmental impacts were not taken into account by the study design?"

In a very short and simplified presentation, this example explains what LCA is, the basic mathematical concept behind it, and how it is carried out in practice.

3.2. Allocation in LCA

Often there are processes along the life cycle of a product or service that provide several functions, e.g., a mine producing multiple products such as copper, silver, and gold. This is referred to as a multi-product process (Frischknecht 2020:59). The environmental impacts of the production processes must then be distributed (allocated) to the respective products. Recycling is a special form of this issue. In principle, recycling is also a multi-product process, but one in which the products occur at different times (Frischknecht 2020:69). However, the various ways of resolving allocation problems are often differentiated between multi-product and recycling allocation. Metals, including gold, often occur as by-products in multi-product systems, e.g., in ore bodies or scrap. Consequently, the environmental impacts of the metal-producing systems must be distributed amongst the metal products. In addition, the allocation of environmental impacts between the first use of the primary material (mining) and the following use of scrap (recycling) is of central importance in the metal industry, including the recycling of gold. Thus, gold can serve as a prime example for many questions raised regarding allocation in LCA.

3.2.1. Multi-product allocation

Multi-product allocation should be managed by the following three successive steps, according to the ISO 14044 (International Organization for Standardization 2020b):

1. avoidance of allocation by dividing or expanding the system;

2. distribution of the environmental impacts to the products via physical properties;

3. distribution of the environmental impacts among the products via other relationships such as product revenues (often called economic allocation).

The first step tries to avoid allocation and can be split into division and expansion. The division of a system means that by examining the processes in more detail, it can sometimes be revealed that products are not, or only partly, jointly produced. This is, for instance, the case for gold production from copper mines (see Figure 11).

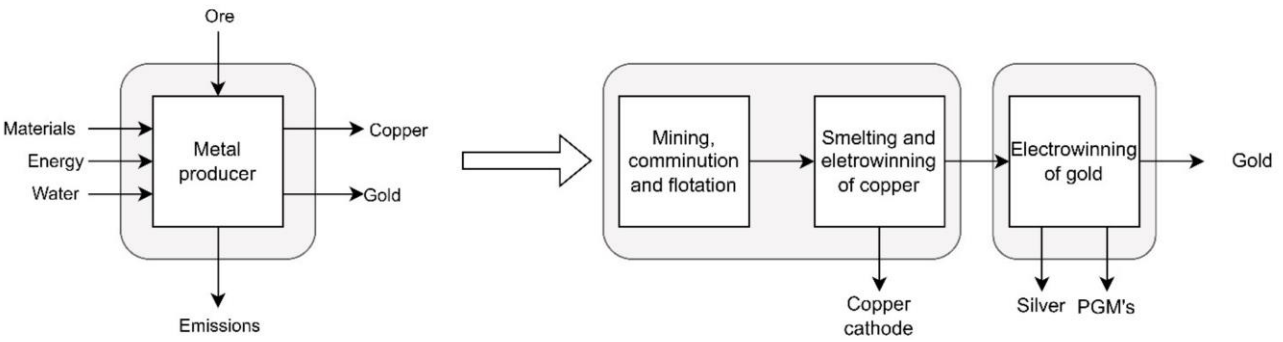

Figure 11: Visualization of division to solve multi-product allocation according to ISO 14044 based on Fritz and Schmidt (2025).

When looking at the product system as a whole, like it is commonly done in a so-called Organizational LCA (O-LCA), it appears as one black box with all inputs and outputs needed to produce copper, gold, silver, and PGMs. In order to make a statement regarding the environmental impacts for each of the products, the total impacts of the organization must be divided between all the products. But, if the black box is further divided into its single processes, it is visible that, e.g., copper cathodes leave the product system at first (Figure 11). Hence, all the further processing steps for extracting gold, silver, and PGMs should not be allocated to the copper. This example also shows that the division in this case cannot solve the allocation problem, as several processes still have more than one output necessary to produce the final products (see Figure 11). Nevertheless, the approach does get a bit closer to a more realistic or fair way of allocating the impacts to the causes.

Expanding the system, on the other hand, always solves allocation, as it simply merges all products into one functional unit—often called the product basket. The problem with the product basket is that LCA is mostly used for comparing different production systems or alternatives, and it is in many cases not possible to find a matching product basket with not only the same products but also the same production quantities. A special case associated with the first step of dealing with allocation, although not described particularly in the main document of the ISO 14044, is the system expansion and substitution (Brander and Wylie 2011). This can be seen fairly often in LCA studies and is hence briefly described. A visualization of the approach can be found in Figure 12.

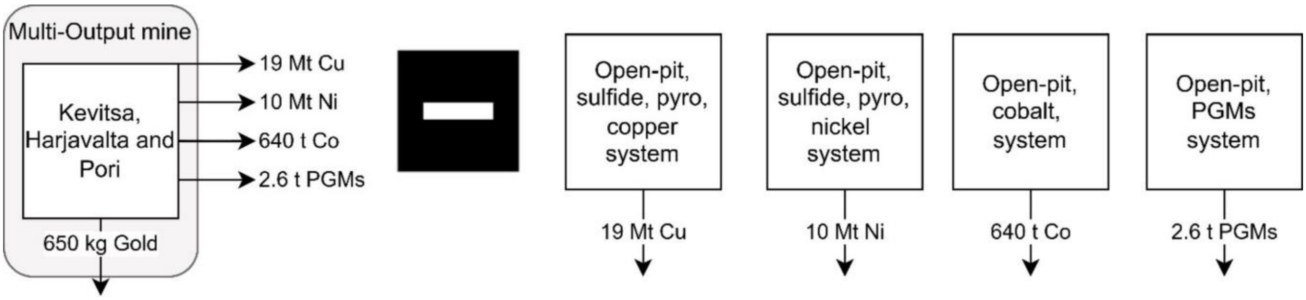

Figure 12: Visualization of system expansion and substitution to solve multi-product allocation based on Fritz and Schmidt (2025).

In system expansion and substitution, the system is first expanded to the whole product basket. Next, single product systems are searched for the products in the product basket, or at least for those that are not the main product of interest. Then LCAs are calculated for these single-product systems, and the environmental impacts are subtracted from the product basket. The main criticism of this allocation method is that the subjective choice of an allocation method is replaced by the subjective choice of alternative product systems (Frischknecht 2000). Additionally, a single-product system is not always available.

The second step, according to ISO 14044, is to distribute the environmental impacts to the products via physical properties. A common example of this is waste incineration. Assuming it was known that one waste stream contains mercury, then mercury emissions and their environmental impacts can be allocated physically to the mercury-containing waste input. In the case of mining, where all the metals typically occur in the same rock, this is seldom possible. A common misconception is that distributing environmental impacts based on physical parameters such as mass or exergy automatically constitutes physical allocation; however, true physical allocation requires a clear cause-effect relationship, where a quantitative change in the products changes the in- and outputs. When looking at example D3 of the ISO 14044 amendment 2, it gets clear that simply using physical quantities as allocation keys is not meant by physical allocation and falls under step 3, distribution via other relationships (International Organization for Standardization 2020b).

The third step of solving multi-product allocation according to ISO 14044, distribution with other relationships, is, in the field of LCA for metals and mining, the most commonly used method (Santero and Hendry 2016). Among these relationships, the most conventional methods are to allocate the total impacts based on the share of product mass or revenue. Allocation by mass means that the same expenses and environmental impacts are allocated to each product per weight. The environmental impacts are distributed to the same extent as the weights of the individual products relate to the total weight of all products. Simply put, the product with the highest production volume gets allocated the highest environmental impacts. Allocation based on revenue (often called economic allocation), on the other hand, means that the impacts are allocated to the products based on the share of each product's revenue of the total revenue. In the case of a base metal mine, mass allocation can be sufficient. For a multi-product mine that produces precious metals like gold amongst base metals, the case can be different. Some copper-gold mines, for instance, are only profitable because of the gold produced although the mass of copper produced, is a thousandfold more. In this case one might ask whether allocation by mass is representing the benefit of the system under investigation, which, in a capitalist world, is often to make profit. Hence, in cases where products with very different values are produced, economic allocation should be considered (Ardente and Cellura 2012; PE INTERNATIONAL 2014).

3.2.2. Recycling allocation

Recycling allocation raises the question of how the impacts should be allocated between the original production (e.g., mining) and the recycling (e.g., gold scrap recycling). A review of allocation methods in recycling by the Swedish Life Cycle Center lists 13 methods (Ekvall et al. 2020). These will not all be presented here, but the two most important concepts will be explained briefly. The two most discussed methods in LCA for recycling are, according to Frischknecht (2020:85f.) the recycled-content approach (cut-off) and the end-of-life (EOL) approach (avoided burden).

In the cut-off approach, the impacts of extracting a resource are allocated to primary raw materials and, thus, to the products that use primary material. The impacts caused by the recycling of scrap are allocated to the resulting secondary raw materials and, therefore, to the products that use these secondary raw materials (Frischknecht 2020:86). This means that the system boundaries of primary production and secondary production are separated, and impacts are not crossing these system boundaries. A schematic visualization of this allocation method can be found in Figure 13.

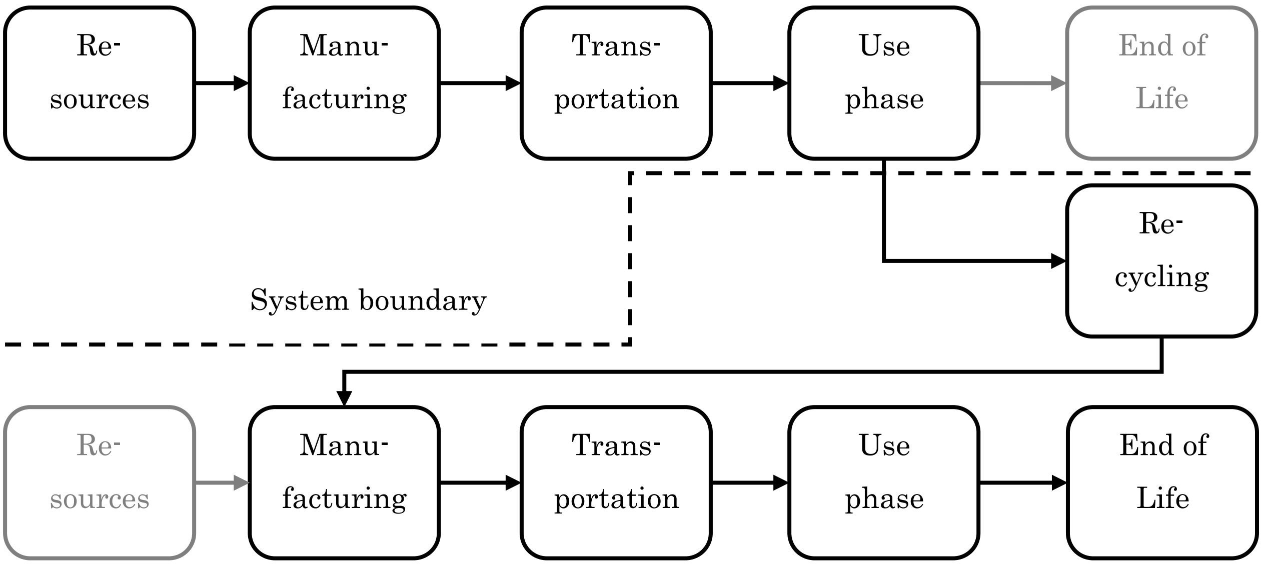

Figure 13: Visualization of the cut-off approach following Ekvall et al. (2020).

This allocation method incentivizes recycling, as long as the recycling has lower environmental impacts than the virgin materials production. This approach is also sometimes called 100-0, as hundred percent of the impacts of the raw material production are allocated to the product using the raw material (Ekvall et al. 2020:23f).

The avoided burden approach, on the other hand, focuses on the fate of materials at the end of a product's life. The proportion of recycled material from a product determines the amount of material that substitutes primary material. Recycled raw materials avoid the degradation of primary material. In this conceptual model, recycling avoids the impacts associated with the extraction of primary raw materials. These avoided impacts are credited to the product system that sends the materials for recycling (Frischknecht 2020:86). A schematic visualization of this allocation method can be found in Figure 14.

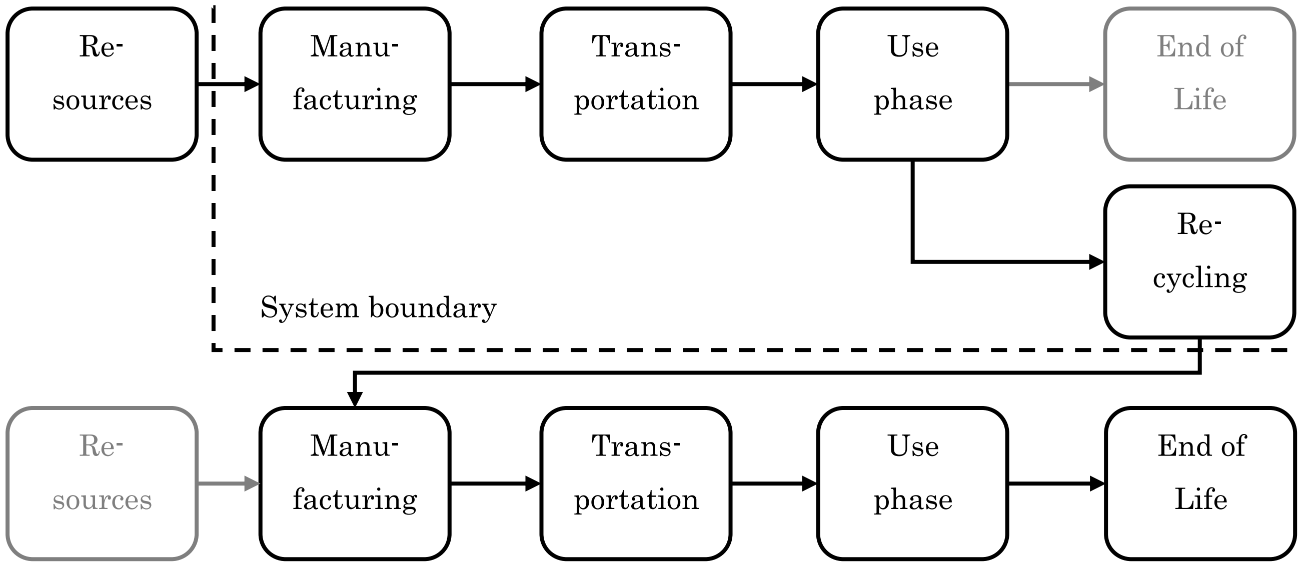

Figure 14: Visualization of the avoided burden approach Ekvall et al. (2020).

The avoided burden approach incentivizes the design-for-recycling, because the impacts for the production from raw materials get lower the more material in the product is recycled (Ekvall et al. 2020:29f). Two special cases of this method often used are called the 0-100 and 50-50 approaches. The first one is the opposite of the aforementioned 100-0 approach, where one hundred percent of the impacts of the raw material production are allocated to the last production cycle before disposal (Ekvall et al. 2020:29f). The latter equally distributes the impacts of primary and secondary production between the producer and user of primary and secondary materials (Frischknecht 2020:87). For visualization of the 50-50 approach, one could imagine moving the system boundary (dotted line) in Figure 14 to the upper left, cutting the resources and the recycling phase in half.

When it comes to gold recycling, gold shows to be a very special material for many reasons. Because of gold's inert material properties, it is very easy to recycle it from various compositions, and the impact of final disposal or dissipation losses to the environment is insignificant. Furthermore, because of gold's value, it is then and now almost always recycled. Thus, neither recycling (cut-off) nor design for recycling (avoided burden) needs to be incentivized.

In the present dissertation, the cut-off approach was chosen for both gold recycling from high-value material and WEEE. For high-value recycling, this was due to the fact that the recycling plants providing the data claimed not to use any primary material, e.g., doré gold. If all the feedstock for producing recycled gold is EOL material, and if one assumes that all the gold output is recycled and has no impacts from final disposal, then avoided burden yields the same results as cut-off. Another essential question when it comes to gold and recycling regards the lifetime of the products. How long does it take for gold products to be returned to CE? It is not unlikely that the use phase of gold products is quite long compared to other products. Using the avoided burden approach leads to a burden shift of mining impacts occurring in the present but being accounted for decades later, when the gold finds its way to recycling again. This burden shift challenges the intergenerational equity principles underlying the Sustainable Development Goals (SDGs), as discussed by Frischknecht (2020:86). Using the cut-off approach for gold from high-value scrap maintains a continuous pressure on primary production facilities to reduce their carbon footprints and promotes the purchase of recycled gold. However, it is crucial to ensure that the material entering the recycling facilities is genuinely EOL scrap rather than misclassified primary gold. A lack of transparency in regard to this could lead to greenwashing within the gold market.

For gold recycling from WEEE, the cut-off approach was chosen, as WEEE is a hazardous material if improperly managed, and hence recycling should be incentivized. Another reason for incentivizing gold recycling from WEEE is because the amount, and hence the value, of gold in WEEE is much lower than in high-value scrap, making it more probable that gold in WEEE is dissipated and lost for CE. Note that for other materials in WEEE, the avoided burden approach could make sense. For example, the plastic fraction is complex to separate from the metals in WEEE and hence is commonly incinerated, probably leading to some environmental impacts like, e.g., CO_2 emissions. In this case, incentivizing design for recycling to reduce carbon emissions from plastic incineration could make sense. But because of gold's inert character it can quite easily be recycled from any mixture, and promoting design for recycling for gold is hence not necessary.

3.3. Uncertainty in LCA

This chapter provides a very brief discussion of common concepts regarding the topic of uncertainty in LCA. This is regarded as the bare minimum needed to make the present dissertation more comprehensible (see section 6). Readers seeking a more comprehensive and in-depth understanding of the topic are encouraged to consult the literature referenced in this chapter—particularly the recent book by Heijungs (2024). The issue of uncertainty has been of controversial debate in the LCA community since the 90s, and there is still no consensus, as was shown in the recently published book *Probability, Statistics and Life Cycle Assessment* by Heijungs (2024). Various methods have been proposed to quantify uncertainty in LCA, like pedigree matrices, fuzzy data sets, analytical uncertainty propagation (Taylor series), Monte Carlo simulation, or Bayesian statistics (Heijungs 2024; Rosenbaum et al. 2018).

By far the most popular method used for uncertainty analysis in LCA is the global sensitivity analysis with Monte Carlo (Heijungs 2024:12). This should not be mistaken for the local sensitivity analysis (Paper VI), where single values in a given LCA model are changed to analyze their sensitivity to certain changes (Rosenbaum et al. 2018). Monte Carlo simulation is a method from stochastics in which random samples of a distribution are drawn repeatedly using random experiments (Harrison 2010). Consequently, Monte Carlo in LCA calculates the LCA models several thousand times, and for each calculation selects a value for each LCI entry that lies within the specified confidence interval of the corresponding data point. This simulation is supported by various of the aforementioned LCA software tools, such as SimaPro (PRé Sustainability B.V. 2025), Sphera (formerly GaBi), Umberto (until v.5), OpenLCA (GreenDelta GmbH 2025), or Brightway (Mutel 2017). In order to perform a Monte Carlo simulation in LCA, the type of distribution and the standard deviation need to be known for each LCI entry. And this is the crux of the matter of uncertainty analysis in LCA. It necessitates substantial uncertainty data, which are in general inaccessible or require significant effort to compile for the often hundreds to thousands of entries within an LCI (Frischknecht 2020:148ff; Rosenbaum et al. 2018). In ecoinvent, a method is used to estimate the standard deviation for each value based on a semi-quantitative approach called the pedigree matrix (Ciroth et al. 2016; Weidema and Wesnæs 1996). In this approach a matrix is generated using a predefined set of quality indicators in the columns and a rating scale in the rows (see Table 2).

Table 2: Pedigree matrix as used in ecoinvent 3 for estimating the uncertainty of LCI entries following Ciroth et al. (2016).

	Reliability	**Completeness**	**Temporal correlation**	**Geographic correlation**	**Technological correlation**
1	Verified data based on measurements	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Less than 3 years of difference to the time period of the data set	Data from area under study	Data from enterprises, processes and materials understudy
2	Verified data partly based on assumptions or non-verified data based on measurements	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Less than 6 years of difference to the time period of the data set	Average data from larger area in which the area under study is included	Data from processes and materials under study but from different enterprises
3	Non-verified data partly based on qualified estimates	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Less than 10 years of difference to the time period of the data set	Data from area with similar production conditions	Data from processes and materials under study but from different technology
4	Qualified estimate (e.g., by industrial expert)	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Less than 15 years of difference to the time period of the data set	Data from area with slightly similar production conditions	Data from related processes or materials
5	Non-qualified estimates	Representativeness unknown or data from a small number of sites and from shorter periods	Age of data unknown or more than 15 years of difference to the time period of the data set	Data from unknown or distinctly different area	Data from related processes on laboratory scale or from different technology

The rating scale in ecoinvent is a five-point ordinal scale (ranging from one to five), and the quality indicators used since ecoinvent v.3 are (Ciroth et al. 2016):

- Reliability
- Completeness
- Temporal correlation
- Geographical correlation
- Technological correlation

The pedigree approach starts with the qualitative evaluation of each entry of the LCI according to the quality indicator, ranging from one to five, with one representing higher levels of certainty and five representing lower levels of certainty. Therefore, the elements U contained within the matrix are numerical values ranging from one to five. In order to facilitate the process of evaluation and reduce the subjectiveness of the evaluation, each cell in the matrix is accompanied by a description. For instance, in the context of geographical correlation, a ranking of two signifies that the LCI entry is derived from average data of a larger area in which the area under study is included (Table 2). The pedigree approach in ecoinvent assumes that the distribution of uncertainty for all LCI values is lognormal. The following formula is employed to calculate the variance, σ^2, and consequently the standard deviation (square root of variance):

Equation 4: Calculation of the uncertainty for LCI values using the pedigree approach according to Frischknecht (2020:150)

$$\sigma^2 = e^{\sqrt{(\ln U_1)^2+(\ln U_2)^2+(\ln U_3)^2+(\ln U_4)^2+(\ln U_5)^2}}$$

The approach using the pedigree matrix facilitates the incorporation of confidence intervals into the final outcomes of an LCA.

The section above focused on uncertainty associated with LCI data. This data can either be primary data based on measurements and interviews or secondary data from literature. In the discussion of uncertainty in LCA, this is referred to as parameter uncertainty, and it is the most discussed topic (Rosenbaum et al. 2018). But LCA has lots of other points that add to the uncertainty of the results, such as freedom in methodological choices, calculation of the characterization factors, or modeling mistakes (Rosenbaum et al. 2018). In Paper I and II of the present thesis, important methodological choices that lead to systematic errors in LCA that cannot be addressed by any of the common statistical tools like Monte Carlo are discussed.

4. Contribution

Paper I: Fritz, Benjamin, and Mario Schmidt. 2021. "Analysis of Life Cycle Datasets for the Material Gold." Pp. 99–112 in Progress in Life Cycle Assessment 2019, Sustainable Production, Life Cycle Engineering and Management, edited by S. Albrecht, M. Fischer, P. Leistner, and L. Schebek. Cham: Springer International Publishing.

I conceived and designed the analysis and developed the idea of visualizing the regionality of the gold dataset from Classen et al. (2009:Part IX). I had the idea of exploring potential improvements to the "market datasets" as represented in the LCA databases Sphera (formerly GaBi) and ecoinvent. For data collection, I did a detailed review of relevant literature, with a particular focus on Classen et al. (2009:Part IX). Analytical tools and data resources were provided by Schmidt, M., who granted access to the LCA software tool Umberto and the ecoinvent database. I performed the analysis by visualizing the regional distribution of the dataset on a world map, and I calculated the improved market mix. The manuscript was initially drafted by me, while the final version benefitted from discussion and advice from Schmidt, M., reviewers, and the editor. Schmidt, M. secured the funding that enabled this research, and he developed the overreaching conceptual framework for the project of gold and LCA.

Paper II: Fritz, Benjamin, and Mario Schmidt. 2025. "Gold from Copper Mining as a Case Study for Allocation in Life Cycle Assessment." Environmental Research: Infrastructure and Sustainability. doi: https://doi.org/10.1088/2634-4505/ade473.

The analysis was conceived and designed by me. I developed the idea of addressing the allocation problem using a case study of copper-gold mining. The idea of asking about the benefit in the context of allocation was inspired by Schmidt (2009). The inclusion of a copper-gold ratio analysis was proposed by Schmidt, M. Data collection involved the use of LCI data for the Kevitsa mine, derived from an earlier collaboration with the German Federal Institute for Geosciences and Natural Resources (BGR) that can be found in Fritz et al. (2023). I extended the LCI data by adding processes for gold refining and gathering all missing information. The LCA database ecoinvent, as well as the carbon database SKARN, were provided by Schmidt, M. I performed all analyses, including the LCA, allocation, and market-price analyses. The manuscript was initially drafted by me, while Schmidt, M., contributed significantly to the structuring, offered constructive feedback, proposed revisions, and helped finalize the manuscript. Schmidt, M. secured the funding that enabled this research, and he developed the overreaching conceptual framework for the project of gold and LCA.

Paper III: Fritz, Benjamin, Bernhard Peregovich, Lorena da Silva Tenório, Adria Cristina da Silva Alves, and Mario Schmidt. 2023. "Mercury and CO2 Emissions from Artisanal Gold Mining in Brazilian Amazon Rainforest." Nature Sustainability 7, 15–22. doi: https://doi.org/10.1038/s41893-023-01242-1.

The project planning was carried out jointly by Schmidt, M., and Peregovich, B., with Schmidt, M., also securing the necessary funding. I had the initial idea of using the mass-balance approach to assess mercury emissions. The final methodology was developed collaboratively by myself, Peregovich, B., and Schmidt, M. On-site data collection in the Brazilian Amazon rainforest was conducted by Peregovich, B., da Silva Tenório, L., and da Silva Alves, A.C. Additionally, Schmidt, M. and I participated twice in two-month stays in the Brazilian Amazon rainforest for data collection. Schmidt, M. provided the LCA database ecoinvent as well as the carbon database SKARN. While analyses were performed by me and Peregovich, B., validation of the results was carried out by Schmidt, M. I drafted the manuscript, with significant contributions and revisions provided by Schmidt, M. He also contributed significantly to the ethics declaration of nature sustainability. Schmidt, M. secured the funding that enabled this research, and he developed the overreaching conceptual framework for the project of gold and LCA.

Paper IV: Fritz, Benjamin, Carin Aichele, and Mario Schmidt. 2020. "Environmental Impact of High-Value Gold Scrap Recycling." The International Journal of Life Cycle Assessment 25(10):1930–41. doi: https://doi.org/10.1007/s11367-020-01809-6.

The analysis was conceived and designed by Schmidt, M. Data collection was initiated by Aichele, C., who gathered primary data from recycling plants. Subsequently, I reviewed and verified the data, clarifying any unclear points, and consolidated the information into a comprehensive LCI. Schmidt, M. provided access to the LCA software tool Umberto and the ecoinvent database, which were instrumental for the analysis. Initial company-specific LCA models were created by Aichele, C., for internal use, and these models significantly helped me with the conceptualization of the final LCA model. I drafted the manuscript, while Schmidt, M., provided essential support in structuring the text, offering constructive feedback, proposing revisions, and finalizing the document. It was Schmidt, M.'s idea to structure the main section by first presenting a gate-to-gate inventory, followed by a cradle-to-gate inventory, and finally the cradle-to-gate LCA results. Schmidt, M. secured the funding that enabled this research, and he developed the overreaching conceptual framework for the project of gold and LCA.

Paper V: Fritz, Benjamin, and Mario Schmidt. 2022. "An Ecological Analysis of the State-of-the-Art Refinery of High-Value Gold Scraps." World of Metallurgy 75(2):84–93.

The idea to submit a paper to the European Metallurgical Conference (EMC) 2021 on the environmental aspects of gold refining originated from Schmidt, M. The concept of focusing on improving the LCA for gold refining, as previously published in Fritz et al. (2020), with a specific emphasis on metallurgical processes, was my contribution. I collected primary data on transport processes and secondary chemical data related to gold refining. Schmidt, M., provided access to the LCA software tool Umberto and the ecoinvent database, which were essential for conducting the analyses. I performed all analyses, created the graphics and diagrams, and prepared the first draft of the manuscript. Schmidt, M. contributed significantly by assisting with the structure, offering constructive feedback, suggesting revisions, and finalizing the text. Schmidt, M. secured the funding that enabled this research, and he developed the overreaching conceptual framework for the project of gold and LCA.

Paper VI: Fritz, Benjamin, and Mario Schmidt. 2025. "Climate Change vs. Circular Economy: Challenges of the Most Common Route for Recycling Gold from WEEE." Sustainability 17(5):2086. doi: https://doi.org/10.3390/su17052086.

The idea of writing a paper on the LCA of the pyrometallurgical recycling of WEEE using the ecoinvent dataset was my contribution. I collected all necessary data for the analysis. Schmidt, M. provided access to the ecoinvent database, which was instrumental for conducting the study. I performed the analyses and created the tables, graphics, and diagrams to visualize the results. I prepared the first draft of the manuscript, which initially placed a stronger emphasis on the societal aspects of WEEE recycling. Schmidt, M. provided valuable advice to refocus the paper on the environmental aspects, thereby streamlining and shortening the article. Additionally, Schmidt, M. offered constructive feedback, suggested revisions, and corrected the final version of the manuscript. Schmidt, M. secured the funding that enabled this research, and he developed the overreaching conceptual framework for the project of gold and LCA.

5. Peer-reviewed articles

5.1. Paper I: Analysis of Life Cycle Datasets for the Material Gold

Fritz, Benjamin, and Mario Schmidt. 2021. "Analysis of Life Cycle Datasets for the Material Gold." Pp. 99–112 in Progress in Life Cycle Assessment 2019, Sustainable Production, Life Cycle Engineering and Management, edited by S. Albrecht, M. Fischer, P. Leistner, and L. Schebek. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-50519-6_8.

This is a pre-copyedited version of a contribution published in Progress in Life Cycle Assessment 2019. Sustainable Production, Life Cycle Engineering and Management by Albrecht, S., Fischer, M., Leistner, P., Schebek, L. (eds) published by Springer, Cham. The definitive authenticated version is available online via https://doi.org/10.1007/978-3-030-50519-6_8.

Analysis of life cycle datasets for the material gold

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Abstract. The representation of gold-producing processes in common life cycle assessment (LCA) databases is insufficient. The biggest problems identified are the missing data for recycling of high-value scraps and for ASM and the estimations in industrial mining. The life cycle inventories (LCI) for the latter are based on corporate reports. The data available from the company figures are always incomplete and must therefore be scaled between the different mines. This process was defined in this work as Intersystemic-Data-Scaling (IDS). An analogy is presumed here between mines, although literature shows that there are differences in mines like ore types that affect the extraction processes and thus the LCI. In the present study all the assumptions and IDS were visualized in a world map. It was found that except for energy demand and production volumes there is no dataset without IDS. Finally, the actual shares of the different gold routes in the world market were estimated using literature research. When compared to the market shares used in common life cycle databases it can be seen that there are big data gaps emphasizing the importance of further data collection for the life cycle datasets for the material gold.

Keywords: life cycle inventories, gold mining, mineral extraction, data gaps, market datasets

1 Introduction

Gold has always been one of the most sought-after precious metals. However, the conditions in which the valuable mineral is mined are often kept quiet**.** Besides its various applications in the investment, jewelry and industrial sector gold also has a bad reputation since it leads to negative impacts that are of great importance—resource depletion, the extensive use of chemicals, toxic emissions, high energy consumption and social concerns, just to name a few.

The gold stock already mined is estimated at approximately 190,400 metric tons or a cube with an edge length of 21 meters in 2018, of which 2/3 were mined after 1950. Of this figure, approximately 73,000 metric tons (40 %) of gold are stored in bank safes and vaults [1]. In 2018, the demand for gold was 1,800 metric tons for investment and 2,600 metric tons for the manufacture of jewelry and industrial goods. In addition, demand has been fairly constant for the last decade [2]. If gold stocks from banks and vaults were used to meet the demand for gold for jewelry and industrial goods, the world could live 28 years without gold from mines. Furthermore one could include some values from the literature on the environmental impacts of gold mining in this thought expiment like global warming potential of gold from mines with approx. 20,000 kg CO_2-equivalent per kg gold (kg CO_2-eq. / kg Au) [3] or Cyanide demand of approx. 140 kg cyanide / kg Au [4]. The environmental impacts of this thought experiment would lead to a saving of incredible 1.5 Gt CO_2-eq or the potential risks of 11 Mt cyanide could be avoided.

With this simplified example, it can be shown how different the discussion on environmental issues in gold production is from other resources. Gold is mainly used for luxury, decoration, status and investment and mainly remains highly concentrated in the system, unlike other mining resources such as coal or metals, which are subject to high dissipation or even chemical transformation. In detail, the application of gold is shown in Fig. 1.

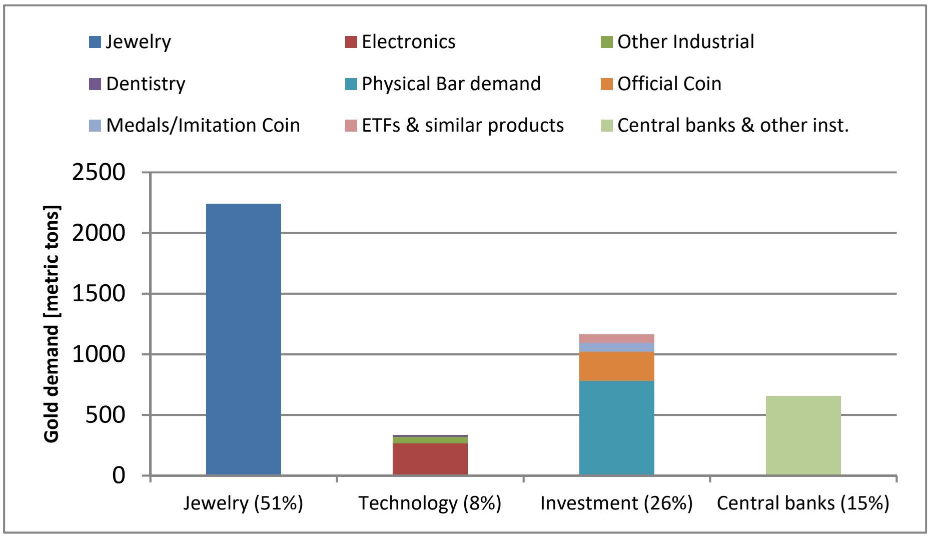

Fig. 1: World gold demand by different applications [2]

The demand for these various applications is covered by the production of gold. There are different approaches to subdivide the different production routes. In the area of life cyle assessment (LCA), it makes sense to subdivide according to process technologies. Fig. 2 below shows the production of gold according to its main process routes.

The ten countries that mined the most gold in 2018 can be found in Fig. 3. In 2005, South Africa, Australia and the USA led the production statistics [5]. In 2018 China, Australia and Russia were the three countries with the largest production of gold from mining [2].

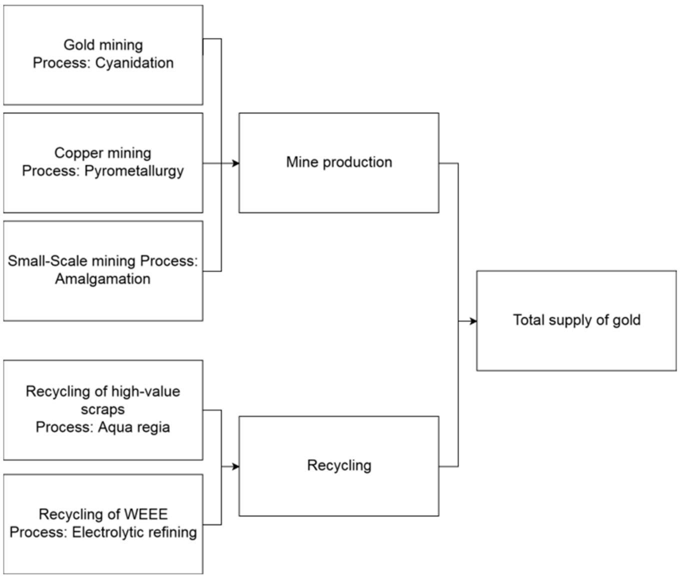

Fig. 2: Gold production by different process technologies

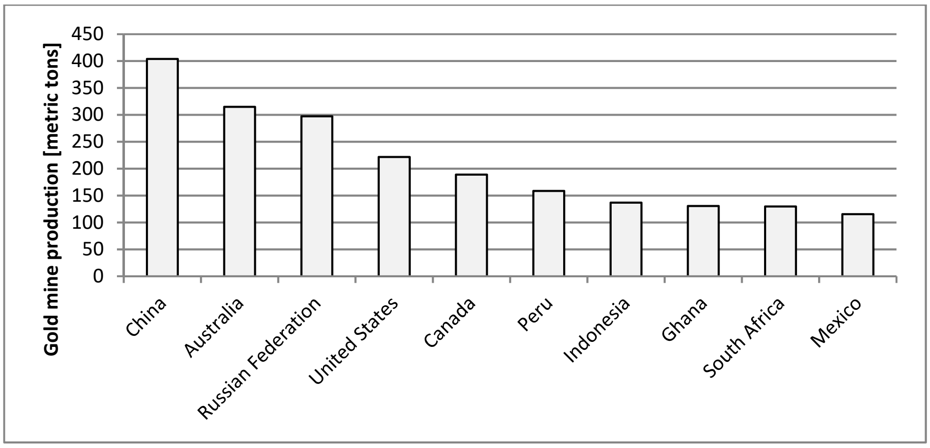

Fig. 3: Gold production in 2018 by different countries [2]

Gold mining is associated with major environmental impacts. This has a major impact on the LCA of electronic products. In a study by Ercan et al. [6] on the LCA of smartphones, gold, based on ecoinvent data, accounts for more than 40 % of the total impact in five of twelve impact categories. An LCA study on notebooks by O'Connell et al. [7] based on GaBi data came to similar conclusions. By far the largest contribution to the GWP is made by the mainboard, in which the gold pins of the RAM bars contribute around 40 %. Even such small amounts of gold, which are used in laptops or smartphones, already have an enormous impact on the overall product. It is therefore important to use the most accurate datasets possible in LCA. This study will therefore analyze the current LCA datasets on the material gold and examine the sources and quality of their content.

2 Methodology

The most widely used LCA databases are GaBi databases from the German company thinkstep AG and ecoinvent from a consortium around the Swiss Federal Institute of Technology Zurich (ETH Zurich). Hence, for ecoinvent, the data transparency is considerably higher due to detailed reports which allows analyzes in greater depth, it was the main source for this research. Nevertheless, some interesting insights from the information that is publicly accessible as well as from private communication with providers could also be gained for the GaBi database. Since the introduction of the first gold dataset in ecoinvent in 2007, all assumptions and improvements from the official ecoinvent reports have been investigated in a systematic literature research. The first report, Classen et al. [8], in which gold appears, was analyzed in detail, particularly with regard to the assumptions and estimates made.

All subsequent change reports were then examined for changes affecting the datasets for gold. The description of the datasets from the databases is divided into the different production routes of gold by process technology (see Fig. 2). **Table 1** also shows a more detailed list of all the change reports taken into account for the literature review.

Finally, the share of production routes in the global market was reviewed in the databases and compared with the actual composition of the gold market.

Year	Author: Title
2007	M. Classen, H.-J. Althaus et al.: Life Cycle Inventories of Metals
2009	M. Classen, H.-J. Althaus et al.: life Cycle Inventories of Metals
2009	H.-J. Althaus, C. Bauer et al.: Documentation of changes implemented in EI Data v2.1
2010	H.-J. Althaus, C. Bauer et al.: Documentation of changes implemented in EI Data v2.1 and v2.2
2013	E. Moreno Ruiz, B.P. Weidema et al.: Documentation of changes implemented in EI Data 3.0
2014	E Moreno Ruiz, T. Lèvovà et al.: Documentation of changes implemented in EI Data 3.1
2015	E Moreno Ruiz, T. Lèvovà et al.: Documentation of changes implemented in EI Data 3.2
2016	E Moreno Ruiz, T. Lèvovà et al.: Documentation of changes implemented in EI Data 3.3
2017	E Moreno Ruiz, L. Valasina et al.: Documentation of changes implemented in EI Data v3.4
2018	E Moreno Ruiz, L. Valasina et al.:Documentation of changes implemented in EI Data v3.5

Table 1: List of all ecoinvent (EI) documentation reports used for the literature research

3 Analysis of common LCA datasets

3.1 Industrial gold mining with cyanidation

The process in GaBi, which represents the globally averaged situation for primary gold, consists of data from South Africa, Ghana, Peru and Australia. These four are among the top ten gold producing countries, accounting for 20 % of world production [2].

In ecoinvent, the data is more comprehensive and can be analyzed in much more depth. The data stems from public reports by the world's most important gold producers in 2005. In addition to the countries Peru, Ghana, South Africa and Australia, which are also included in GaBi, Canada, Chile, Papua New Guinea, Sweden, Tanzania and the USA were included in ecoinvent as well. In gold mining, it is common practice to also publish technology and environmental reports along with the financial ones. With a combination of these three, it is often possible to derive some data such as electricity and water consumption or the quantity of explosives per quantity of gold produced. Normally, not all relevant data is available for every mine. In ecoinvent this problem is solved by transferring existing data from one mine to missing data of another mine. The reference value is usually the quantity of gold or ore mined. This means that some of the values in the life cycle inventories (LCIs), such as chemicals or emissions are adjusted from another source than the original mine by scaling them according to production volumes. In other words, ecoinvent assumes an analogy between the different mines. In this work, this process will be referred to as Intersystemic-Data-Scaling (IDS).

It is obvious that not all mines are identical and consequently assumptions and simplifications have to be made in the field of LCA. However, for mines some differences have a greater impact on LCI-relevant data than others. For example, underground and surface mines differ in their energy requirements due to differences in ore content and additional energy requirements for ventilation of the underground mines [9]. Refractory and non-refractory ores differ greatly in the preparation of the ores necessary for cyanide leaching and thus in the results of the LCA [10]. Moreover the LCA results are affected by the fact of whether and what by-products are produced in a mine. Besides differences in processes, the often discussed allocation problem plays an important role here [11]. Last but not least, the level of technological development and environmental policy in a country also has an influence on the environmental impact of mines [12].

A closer look at the data reveals that the most complete dataset is gold production [ZA] in South Africa. However, for five of the total of nine country-specific gold production processes, more than half of the data stem from non-original datasets and therefore have more than 50 % IDS. As an example the dataset of gold production [CL] in Chile has 85 % IDS and consists apart from the production volume of gold and the level of energy consumption only of data from other mines in South Africa, Peru, Papua New Guinea and Sweden. Does such a dataset actually still reflect the specific gold production of a country? It is a common procedure in science to make well-founded assumptions, analogies and estimates. Especially in the field of LCA, where the calculated results are often only correct in the order of magnitude, but not to the last decimal place, such an approach can be applied. However, the term "gold production [CL]" suggests to the user that this is a dataset on gold production in Chile and not one based largely on data from other countries. It would make more sense to speak of a generic dataset representing e.g. a specific technology.

Looking at the individual LCIs by material category, it can be seen that the most IDS are found in the material type “chemicals”. For the materials zinc and activated carbon, all data points of the nine countries represented in the datasets were scaled on the basis of a doctoral thesis by Stewart [13] in which mines in South Africa were investigated. The same applies to the disposal of tailings. Here, all data points are taken from the Sustainability Reports of two mines in Papua New Guinea that were formerly operated by Placer Dome Inc. But both of these mines used a rather uncommon practice because the tailings were disposed of in water. Especially the topics “tailings” and “chemicals” enjoy great media attention. The widely quoted study by earthworks [14] stated, for example, that a wedding ring produces approximately 20 tons of toxic waste. Exactly these figures should be used with caution and, if necessary, questioned.

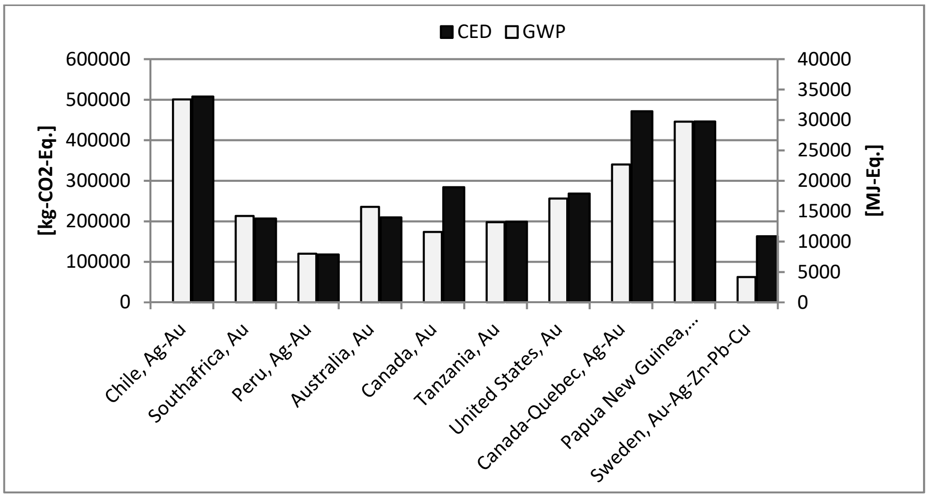

Fig. 4: Comparison of GWP and CED (per kg gold) for mining datasets of different countries

The example of the mines in Papua New Guinea can also be used as an example to pick up again the question of analogy between different mines. The two mines in Papua New Guinea, a country that has often been criticized for its environmental policy in mining, are two open-pit gold-silver mines with relatively small production volumes and mainly refractory ores [15, 16]. Based on this dataset, IDS is now applied on various other mines in different countries. When performing an environmental analysis to compare the Global Warming Potential (GWP) and the Cumulative Energy Demand (CED) for the datasets of all countries (see Fig. 4), the results are very different. Since GWP and CED in mining are mainly dependent on energy demands and these are the only values that were available for all datasets in the environmental reports without IDS, this picture is not particularly surprising. It supports much more the statement that there are large differences between the different mine datasets, which is why the analogy assumed by ecoinvent for many of the materials should be critically questioned.

All IDS are displayed on a world map in Fig. 5. This Figure underlines impressively the influence of the mines in South Africa and Papua New Guinea on the LCI's of the other country specific datasets. Furthermore, one can see that there is not a single dataset that does not include IDS. It is also apparent that no IDS for production volumes and energy demand for mining were performed since these values were available in all the environmental reports of the mines. Data on CO_2 emissions from explosions and the quantity of machines and buildings are missing for all mines and have therefore been scaled from literature values to all mines on the basis of the quantities of gold or ore produced. For refining, energy data were missing for six countries, which is why ecoinvent estimated an energy consumption of 1.63 kWh / kg Au according to literature values by Auerswald [17] and Renner [18].

3.2 Generic gold from world market

Both GaBi and ecoinvent contain datasets that are supposed to represent gold from the world market. Market activities try to model a generic product by taking into account the globally averaged situation, focusing on the main technologies, the region specific characteristics and / or import statistics. Here, the routes shown in Fig. 2 and the production countries shown in Fig. 3 are included by world market share. In both databases the data for ASM are completely missing. Also for the route of high-value gold scrap recycling there are currently no data available. In GaBi the route appears in its market activity with a share of 27 %, but it is assumed as a simplification that high-value gold scrap recycling is only a melting process of gold (private communication). Until ecoinvent v.3 this data gap was closed by assuming that Waste Electronic Equipment (WEEE) recycling has the exact same impact as high-value gold scrap recycling and has a market share of 30 % [19]. In ecoinvent v.3.5 high-value gold scrap recycling was omitted, so that the share is 1 % from WEEE and 99 % from mining (private communication). According to Adams [20], a common process for high-value gold scrap recycling is hydrometallurgical treatment with aqua regia. In ecoinvent the above-mentioned process of gold from WEEE recycling is based on data from a plant in Sweden and contains besides the production volumes only IDS. All the LCI data of this dataset, like energy consumption or emissions is based on assumptions and literature values of furnaces and electrolysis plants. In the GaBi database there is a value for WEEE recycling but the process is not included in the documentation. The GaBi database has a process which represents the production of gold from copper ores with a market share of 20 %. The data is based on a plant by Copper Refineries Ltd. in Townsville, Australia, which first electrometallurgical refines the copper and then extracts the gold from the anode slimes by chlorination. In ecoinvent this route is not shown separately, but one of the mines considered in the datasets for gold production from mining is a copper mine with a copper smelter (see Fig. 5). An overview of the quantities of the individual routes in the market activity of ecoinvent and GaBi can be found in Fig. 5.

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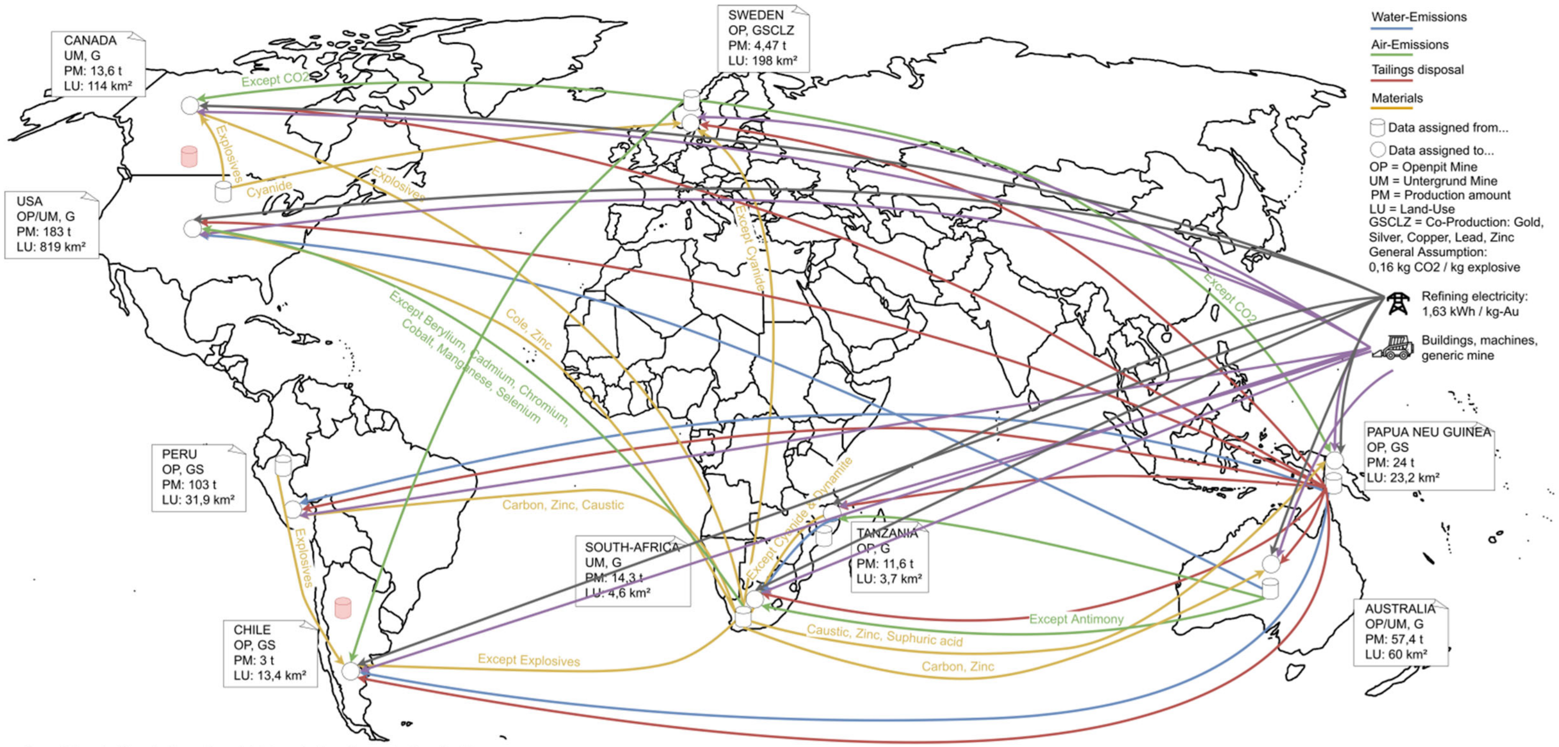

Essential productflows in the ecoinvent database for the mine production of gold.
Own figure based on Classen, Althaus, et. Al. (2009) LCI of Metals

Fig. 5: Intersystemic-Data-Scaling of ecoinvent dataset for gold mine production displayed on a world map

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In the following it shall be attempted to estimate the actual shares of gold production by different process technologies on the basis of literature and market statistics. An annual worldwide mine production of 3,501 metric tons and a production from recycling of 1,168 metric tons is assumed [2]. Furthermore, a market report by World Gold Council [21] referring to the study by Alistair et al. [22] states, that recycling is divided into 90 % from high-value gold scrap and 10 % from electronic waste (WEEE). For ASM there are many different studies with different estimates. In the present work the estimation by Seccatore et al. [23] was used because it is the only study identified that explains in detail and very transparent how the estimation was done. The study comes to a value between 380 - 450 metric tons. Since the gold price and the mining areas increased since 2014 it can be assumed that production most likely increased since 2014 and therefore the upper value of 450 metric tons was chosen [5, 24]. It is difficult to determine how many of these 450 metric tons from ASM is accounted for in the official market statistics and how much is sold on the quiet. Based on personal discussions with experts and own observations from ASM gold mines in the Brazilian Amazon rainforest, it can be assumed that a large part of this gold is traded outside the official world market. For this study it is assumed that 50 % of the ASM is sold on the official markets and therefore the total mine production of 3,501 metric tons has to be increased by 225 metric tons.

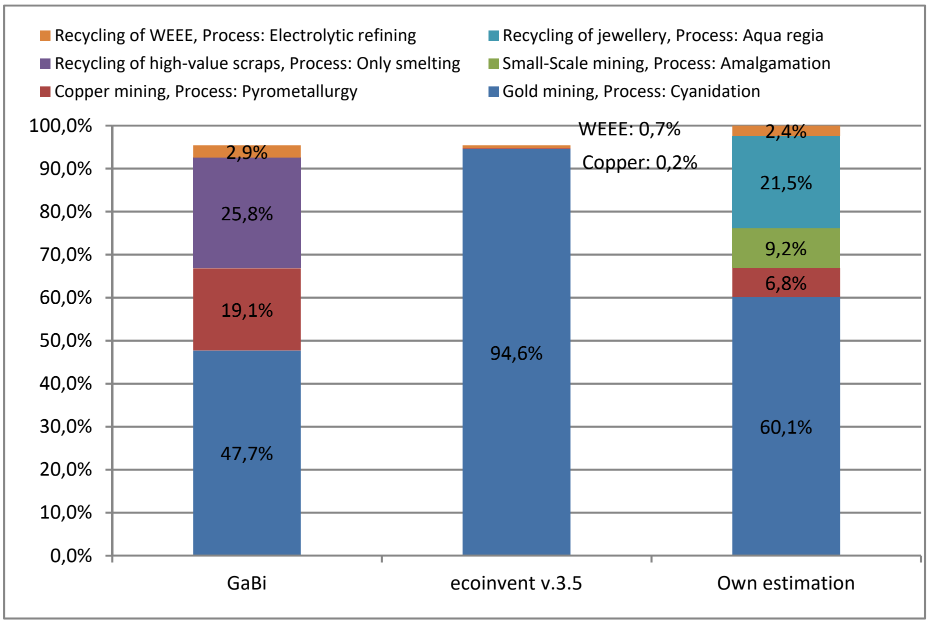

Fig. 6: Comparison of global shares of different gold production processes in different LCA databases with market and literature values. To illustrate the amount of gold from ASM traded outside the official world market the bars *GaBi* and *ecoinvent v.3.5* sum up to less than 100 %.

According to Butterman et al. [25] the proportion of gold from copper concentrate is between 5 and 15 %. Again the higher value of 15 % was chosen as since 2005 the gold price and the Chinese production have increased. In Fig. 6 the results of the estimation on the actual shares of gold production by its different process technologies compared to their representation in LCA databases are shown. Note that the bars representing the database of GaBi and of ecoinvent v.3.5 are lower than 100 % due to the amount of gold produced by ASM traded outside the official world market.

4 Conclusion

Gold has a very bad image from a social and environmental perspective. To quote an outlook on gold in Nature magazine in 2012 goldmining was called "unwanted neighbor" and "Gold not green" [26]. Recent reports from Brazil do not give a better picture of the social conditions of gold prospectors and of the decimation of the rainforest.

Looking at LCA of products, e.g. electronic products, gold has a very high environmental impact even in very small quantities. But gold comes from different production routes and countries, whose social and ecological problems are very different. The most important production routes for gold are: mining with cyanidation, pyrometallurgic refining of copper ores, small scale mining with amalgamation, recyling of high-value scraps with aqua regia and electrolytic refining of WEEE. In the context of this article, these different routes were examined in more detail and their inclusion in the most widely used LCA databases GaBi and ecoinvent were examined.

The dataset for gold mining with cyanidation is in the GaBi database based on datasets from four countries while in ecoinvent there are nine. These data records in ecoinvent originate exclusively from company reports and literature values. The majority of these company figures are no longer publicly available and cannot be verified. The data available from the company figures are always incomplete and must therefore always be scaled back and forth between the data of the LCIs. In this study, this is referred to as Intersystemic Data Scaling (IDS). All these assumptions and IDS for all nine country datasets on gold mining were graphically depicted on a world map (see Fig. 5). In this graphic presentation one can see how dominant the datasets of the mines in South Africa and Papua New Guinea are for chemicals and tailings disposal. Apart from the fact that many of the company figures can no longer be found today, there is another problem with the company figures. Classen et al.[19] describe this problem as follows: "Data in this report are based mostly on environmental reports of large multinational companies. However, it must be assumed that these sources represent rather the best practices for gold mining".With ore grades ranging from five to 40 grams of gold per ton of ore one can see two things. First, for even tiny amounts of gold huge pits or deep shafts have to be dug which needs a lot of energy. Second, different gold mining operations can have very different environmental impacts. Therefore inaccurate data has huge impacts on the results of different LCA studies containing the material gold.

For gold from copper ores GaBi has a specific dataset for the electrolytic treatment of anode slimes. In ecoinvent there is no specific dataset for this, but one of the mines in the dataset for gold production from mining is a copper mine which produces gold only as a by-product. This studied showed that the gold from copper ores makes up for around 7 % of the worlds gold production.

Gold from Artisanal & Small-Scale Mining (ASM) is not found in any of the LCA databases, although it plays a major global role and there are many studies in the field of environment and sustainability on this topic. In ASM, other and additional environmental impacts such as mercury emissions or sediment inputs into rivers are most probably a big problem and therefore further work needs to be done to integrate these process routes in LCA databases [27, 28].

In ecoinvent, the process that represents gold from WEEE recycling is based on the production volumes of a plant in Sweden. All energy consumption and emissions of furnaces and electrolysis plants are based on assumptions and literature values [19]. Especially this topic is getting a lot of attention right now by scientists and also the media although it is only responsible for about 10 % of the amount of gold produced from recycling. The other 90 % stems from recycling of jewelry, coins and other so called high-value gold scrap.

There is currently no LCA data record for high-value gold scrap recycling. GaBi assumes a simple melting process for this in its market activity and ecoinvent has omitted this route. The literature shows that a common process for this is hydrometallurgical treatment with aqua regia. Our results show that this route is responsible for more than 20 % of the worlds gold production. The environmental impacts of this route on the other hand compared to WEEE and/or any mining activities are most probably significantly lower. Simply because the gold content of the input material is already much higher.

In most cases, the value chain of gold is not known, which is why LCA practitioners often use the generic LCA processes also referred to as market processes for their product LCA’s. If one takes a look at the examples of product LCA's mentioned in the introduction where even the smallest amounts of gold have a significant effect on the examined products, it is important to analyze and understand these generic datasets. On the basis of market statistics and literature research, an attempt was made to estimate the actual market shares of the different gold routes as transparently as possible. When compared to the market shares used in GaBi and ecoinvent it can be seen that there are big data gaps emphasizing the importance of further data collection for the life cycle datasets for the material gold.

5 Outlook

To develop a full picture of the environmental impacts of the material gold, additional studies will be needed in the field of life cycle assessment in relation to gold. More primary data is needed on mine extraction in different countries and on possible recycling routes. There is still no data published on the recycling of high-value gold scraps, which accounts for at least 20 % of the gold produced worldwide. The ecoinvent data on gold from WEEE recycling are based on incomplete data from only one recycling plant. New and reliable data must also be collected in the field of industrial mining, especially for the disposal of tailings and the use of chemicals. Both the ecoinvent and the GaBi dataset on gold from mining have one thing in common: the data are based almost exclusively on voluntary company reports and must therefore be viewed very critically. The frequent discussion on spatial differentiation in life cycle impact assessment (LCIA) to increase the environmental realism of LCIA is particularly relevant in the field of mining [29]. The Chinese market, for example, is missing in the databases even though it has been the world's largest gold producer for years now and according to Chen et al. [30] is associated with almost double the GWP then commonly used values. The lack of countries such as Burkhina Faso or Brazil, which are among the top 20 most gold producing countries and where ASM is important, also shows how important it is to collect ASM data. So far, three LCA studies on ASM gold in Peru and the Philippines have been identified [31–33]. In order to close this gap and include these data in common datasets, it is important to collect more data in different regions. Further research is also needed to determine the market share of ASM of gold as accurately as possible. This is also part of a more general problem of transparency in the value chains of gold that could be solved e.g. by using blockchain techniques.

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5.2. Paper II: Gold from Copper Mining as a Case Study for Allocation in Life Cycle Assessment

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PAPER

Gold from copper mining as a case study for allocation in life cycle assessment

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Abstract

Allocation in multi-output life cycle assessment (LCA) systems has been extensively discussed in literature. Common approaches to address allocation include system subdivision or expansion, physical cause-and-effect relationships, and distribution based on allocation factors such as product mass or revenue. In this study, we critically examine these allocation methods using the example of the Finnish copper–gold mine Kevitsa. We demonstrate that the prioritization of allocation methods prescribed by ISO 14044 is often inapplicable. We argue that this issue is partly rooted in the strong association of LCA with natural sciences, such as environmental science, toxicology, mathematics, and physics. This alignment frequently results in allocation choices that fail to reflect the benefit of the product system, as benefit is not an inherent property of a material but rather a subjective preference within the economic system. For illustration, we use CO_2 as a numerical example in one impact category, though allocation plays an equally important role across all impact categories. Moreover, we contend that for processes producing a primary product alongside valuable by-products, a case differentiation instead of a rigid hierarchy should be considered—a perspective not adequately captured by the current allocation standard. We advocate for a more transparent and comparable allocation framework in LCA that prioritizes the benefit of the product system over strict adherence to natural laws.

1. Introduction

A simple 18-karat gold ring weighing approximately 4 g contains about 3 g of pure gold. In some of the world's highest-producing gold mines, such as Olimpiada or Grasberg, the ore grades are typically around 2 g-Au t^{-1} ore. This implies that to produce a single gold ring weighing just four grams, small enough to be worn on a finger, approximately 1.5 tons of ore must be extracted. This figure excludes the additional overburden and gangue material that must also be moved. By contrast, to produce an equivalent mass of copper, only 0.5 kg of ore is required, assuming a copper grade of 0.6%. It is also common for mines to extract multiple metals simultaneously, such as copper and gold, making them multi-output operations. Around 10% of the gold production between 2018 and 2021 came from copper mining, i.e. mainly from porphyric deposits [1]. Furthermore, at least 44% of the global copper mining production is associated with gold [2].

The extraction of such a vast amount of rock for a small quantity of gold comes at a significant environmental cost. Large-scale mining operations necessitate the excavation of deep shafts or the creation of expansive craters, processes that require substantial energy inputs. Additionally, the extraction of gold often involves the use of toxic chemicals, such as cyanide or mercury. The process also demands considerable amounts of water and the use of explosives, further exacerbating the environmental impact.

In response to growing consumer awareness regarding the environmental and ethical implications of gold production, there has been an increasing demand for transparency in the origins and production methods of gold. The gold industry has responded to this trend, with jewelry companies offering 'green' or 'fair' gold, certified by various eco-labels.

One effective method for generating the data required to compare the environmental impacts of different mines and metals is life cycle assessment (LCA). LCA is a well-established methodology used to evaluate the environmental impacts associated with all stages of a product's life cycle. One widely recognized application of LCA is in the assessment of climate impacts, often expressed as CO_2-equivalents (CO_2eq).

SKARN Associates provides a comprehensive database that includes information on energy demand and climate impacts for more than three thousand mining assets producing various metals, including gold, copper, and nickel [3]. A closer examination of the SKARN database reveals that the same mining assets, such as Grasberg, exhibit higher total environmental impacts in the copper database compared to the gold database, with climate change impacts being approximately 1.4 times greater. This discrepancy is primarily due to the allocation methods employed.

Allocation in LCA refers to the process of distributing environmental burdens across the different products generated by a production system. For instance, if livestock farming is responsible for 9% of global greenhouse gas emissions, how should these emissions be apportioned among meat, milk, and leather [4]? Similarly, in metal production, whether from mining or recycling, production systems often yield multiple metals. Therefore, the analysis and application of allocation methods in multi-output systems are crucial for ensuring the accuracy and relevance of environmental assessments and sustainability strategies within the metals and mining industry [5, 6].

The problem, that is also responsible for the aforementioned curiosity in the SKARN database with different impact results for the same mine for different products, stems from the different ways of dealing with these multi-output systems. Different allocation methods have been debated since the 90s [7–11]. In 1997, LCA was standardized by DIN EN ISO 14040 and 14044.

The DIN EN ISO 14044:2021-02 (all references to ISO 14044 in this work, unless stated otherwise, refer to this version) defines three steps for co-product allocation. These steps are in ascending order solving of the system's multifunctionality by subdivision or system expansion. Allocation of unwanted in- and outputs to the specific causes of these outputs via physical laws. The last step, according to ISO, if the prior two have failed, is to allocate the environmental impacts based on distribution keys to the products.

The ISO 14044 is widely accepted as guidelines for allocation in the metals industry, as can be seen in a study by PE INTERNATIONAL on behalf of 16 different industry associations in the field of metals and mining [12]. Additionally, a study by Lai *et al* found that of 27 LCA studies in the field of metals and mining, economic allocation was most widely used, while only two studies used allocation methods not covered explicitly by the ISO 14044 [5]. Furthermore, the authors applied five allocation methods to a Cu–Zn–Pb–Ag mine. The study found that using production costs instead of product prices yields similar results, but they claim that this method might be more robust as it is not dependent on volatile economic prices.

Nuss and Eckelman highlight significant differences for many metals between mass and economic allocation, as well as the relatively low influence of different time spans used for moving-averages of the prices [13]. A review of LCA studies in the metals and mining industry by Santero and Hendry identified several areas of alignment, including allocation [6]. Their tables 1–3 present different allocation recommendations depending on the type of metal, data availability, and product mix. The authors argue that economic allocation captures the driver of the mine, which is making profit. This was also described more generally and not tailored for metals and mining by numerous other studies [14–16]. Many studies additionally suggest using economic allocation when the prices of the products are differing vastly [12, 14, 17–19]. In their case study, Fernandez *et al* applied four different allocation methodologies to an ironmaking process co-producing zinc and slag [20]. To demonstrate the practical implications of the allocation problem, the authors explain differences in the interests of co-product users and producers regarding their choice of allocation methods. They could not find an allocation method that is a good compromise for producers' and consumers' needs. Some studies commonly advocate for harmonizing allocation methods for co-products to achieve more comprehensive and reliable LCA results [5, 6, 20].

The authors of the presented paper share the view that the ISO standard, which remains widely used and frequently cited to justify allocation decisions in LCA, inadequately addresses the core issue of allocation—specifically, the challenge of assigning costs (e.g. environmental impacts) to benefits (e.g. products). The hierarchy of allocation methods recommended by the ISO standard prioritizes so-called 'physical allocation methods' over alternatives such as economic allocation. This prioritization likely reflects the influence of engineers and natural scientists within the LCA community and the ISO, who tend to favor a 'natural law' or, rather, an objective view [21, 22].

The following study does not seek to reach a definitive conclusion; rather, its objective is to provide a concise summary of the key methodological issues pertaining to economic allocation while also offering a comprehensive overview of the current state of the debate. Moreover, it looks at different allocation methods using the impact on climate change from copper–gold production as a prime example and tries to answer the following question: How do allocation methods in LCA, which aim to establish objective rules, represent product systems that are primarily operated for economic reasons (e.g. copper–gold mining), particularly given that economic benefit is not an inherent property of a material but rather a subjective preference within the economic system?

2. Materials and methods

2.1. Solving multi-functionality in LCA

In metals and mining LCA, it is common to encounter systems with multiple products. These systems include ores containing multiple metals that are extracted and refined by mines and smelters or electronic devices containing various metals that are recycled and refined from waste electrical and electronic equipment (WEEE). In these cases, the environmental impacts are jointly caused by all products, but often the aim is to determine the environmental impact of a specific product.

According to ISO 14044, the methods to address the multi-functionality of LCA systems are divided into three main steps. The first step, with its two sub-steps, aims to avoid allocation. The second step attempts to allocate impacts according to their specific causes. Step three involves allocating the impacts using different distribution keys among the products.

The first sub-step, known as subdivision, involves breaking down the product system into more granular process steps to assess whether allocation is necessary. If this approach does not resolve the allocation issue, ISO suggests moving on to system expansion. In this method, the outputs or functional units of the multi-output system are consolidated into a so-called product basket. This means that all the products, along with their specific production volumes, become part of a single functional unit, eliminating the need for allocation.

A peculiarity in comparative LCA is that this method is often extended in ways not explicitly described in the ISO standard. Since the product basket might not be comparable to other systems and LCAs, products from other systems are added or subtracted to match the functional unit. For example, if a smelter 'CN' produces 20 units of copper and two units of nickel, and the study is focused on copper, a common approach is to find another smelter 'N' that solely produces nickel. The environmental impacts of this nickel smelter 'N', scaled to two units of nickel, are then subtracted from the copper–nickel smelter 'CN', resulting in a hypothetical mono-output copper smelter producing 20 units of copper.

In step two, it is recommended to identify the causes or reasons behind the impacts and then associate these accordingly. This can be challenging, especially if there are overhead processes involved. However, in cases where specific emissions happen because of particular inputs, like in waste treatment, this method offers an optimal solution to allocate impacts (e.g. emissions) based on their specific causes (e.g. specific type of waste). ISO 14044 refers to this as 'physical relationships'. In LCA, this is often mistakenly equated with finding distribution keys based on physical parameters. Distributing the total environmental impacts of a product system to each product based solely on physical attributes, such as product mass or crustal concentration is frequently labeled as physical allocation [6, 23, 24]. However, this remains a distribution key and not a true physical cause-and-effect relationship, and therefore, it falls under the next step—step three.

If the previous methods are unsuccessful, ISO recommends step three—allocating the impacts between the products using distribution keys. The most common distribution keys in metals and mining are the weight share of each product relative to the total product weights (mass) or the revenue share of each product relative to the total product revenue (economic).

2.2. Case study: Kevitsa mine, Harjavalta smelter and Pori refinery

The Kevitsa Mine, operated by the Boliden Group, processes surface-mined sulfidic copper ore for pyrometallurgical treatment. The concentrate is transported by train from the mine to the Harjavalta smelter, which is around 900 km away. In Harjavalta, nickel matte and copper anodes are produced. The copper anodes are then transported by train (30 km) to the nearby copper refinery in Pori. There, cathode copper, gold, palladium, and platinum are produced. The mine and its associated refineries are operational at the time of this study (2024) [25]. The annual production comprises approximately 9 million tons of ore, yielding 19 kt of copper, 10 kt of nickel, 640 t of cobalt, 1.5 t of platinum, 1.1 t of palladium, and 650 kg of gold [26 suppl. VII.V]. A block flow diagram of the product system can be seen in figure 1.

A comprehensive LCA of the Kevitsa Mine system was previously developed and assessed by Fritz *et al* [26]. The life cycle inventory data was provided and assessed by the German Federal Institute for Geosciences (BGR) during a project from 2019 to 2022 and published in [26 suppl. VII]. Additionally, the inventories, assumptions, and results were reviewed by a panel with strong expertise in LCA, mining, and metallurgy during the project. This LCA has been expanded for the present paper to include the gold refining process at

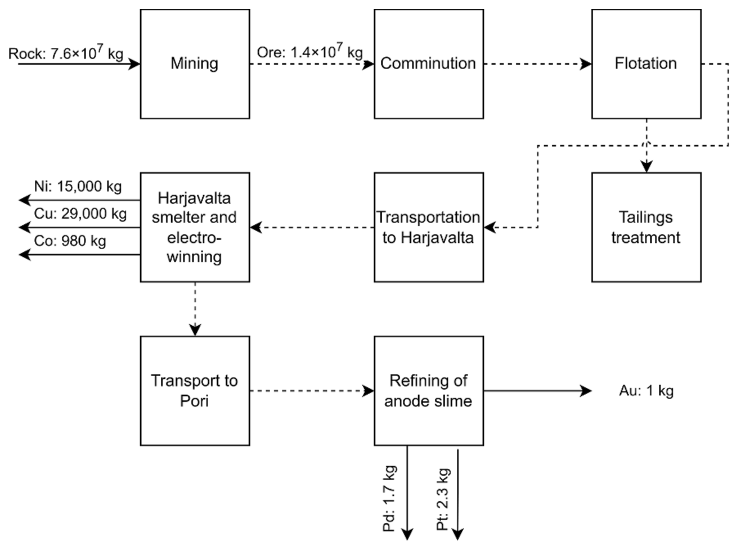

Figure 1. Block flow diagram for the production of 1 kg of gold from Kevitsa mine, Harjavalta smelter and Pori refinery.

the Pori refinery. In this paper, the LCA serves primarily as a case study to explore allocation methods and is therefore not discussed in exhaustive detail. Because allocation affects all impact categories, one exemplary category was chosen, and hence the presented study utilizes impacts on climate change in CO_2eq. The LCA was modeled and calculated in Brightway [27] and ecoinvent [28] using the environmental footprint 3.1 method [29].

2.3. SKARN database

To contextualize the results of this study for copper and gold, the SKARN database was utilized. Skarn Associates is a database provider dedicated to assisting the mining sector in mitigating its negative environmental impacts by providing strategic insights into energy usage, climate change, and water impacts across supply chains.

SKARN predominantly sources its data from mining company reports. The database internally ranks the confidence level of the data based on these reports. The highest confidence is assigned to mining companies that provide detailed reports on energy consumption, CO_2eq emissions, and production volumes. Lower confidence is attributed to assets that only report energy demand, requiring an estimation of CO_2eq, or where only historical data is available. Some assets are benchmarked, meaning that emissions and energy demands from similar assets are scaled according to production volumes. This study used the Q4 2022 (reference year 2020) version of SKARN's database, focusing on energy use and climate change data for copper and gold.

The gold database comprises data on approximately 480 gold mining assets. For these assets, the database includes information such as production volumes, total CO_2eq emissions, and energy demands, as well as specific CO_2eq and energy intensity per unit weight of gold. Additional information is provided on mining methods (e.g. open-pit, underground) and energy sources. For mines producing more than one product (multi-output systems), SKARN employs 'metal-equivalents' to allocate data per unit of gold, resulting in the same outcomes as economic allocation.

The copper database contains data on approximately 259 copper mining assets with similar types of information as found in the gold dataset. Some assets are included in both databases; however, as previously noted in the introduction (section 1), the total CO_2eq and energy demands for the same asset differ between the copper and gold databases. This discrepancy arises from a distinct method of impact allocation. According to SKARN, for mines producing gold within a base metal concentrate, all emissions associated with the freight, smelting, and copper refining of the concentrate are allocated to the primary metal in that concentrate (e.g. copper in a copper concentrate). Nonetheless, emissions from the refining of anode slimes derived from copper refining are calculated and included in the CO_2eq of gold. Since SKARN allocates one specific process, namely the copper smelting, solely to one product, namely copper, this method is, within this study, called process-specific allocation.

To enhance the comparability and contextualization of the results of this study's case analysis, certain modifications were applied to the SKARN database. Specifically, for all copper–gold mines, the total CO_2eq values from the copper dataset were compared with those from the gold dataset. Next, the higher total CO_2eq value from the copper dataset, including the emissions of the copper smelter, was selected. Using this value, both economic and mass allocation were performed based on the specific product volumes of each asset. This resulted in outcomes derived from three distinct allocation methods: the original process-specific allocation provided by SKARN, mass allocation, and economic allocation.

3. Results and discussion

3.1. Subdivision

Boliden reports annual metal production and associated CO_2eq emissions at the company level (organizational LCA, O-LCA), separated into categories for mines and smelters [25]. These emissions can be allocated to the metals produced, either by mass or by economic value. The metals produced by Boliden are zinc, copper, nickel, lead, gold, silver, and palladium. For the mines, mass allocation results in 0.87 kg CO_2eq per kg of metal. For the smelters, the mass allocation yields 0.23 kg CO_2eq per kg of metal. The total carbon footprint of the metals produced by Boliden is 1.1 kg CO_2eq per kg of metal. Note that not all the metals in the concentrate of the mines get produced by the smelter. Metallic cobalt, for example, is not a product of the Boliden smelters but only part of the ore concentrates of some mines. Hence, the smelters' CO_2eq do not get allocated to cobalt. Under economic allocation, the carbon footprint for some metals is increasing, e.g. gold with 10 000 kg CO_2eq per kg of gold. For other metals, the carbon footprint is decreasing, e.g. lead with 0.47 kg CO_2eq per kg of lead. The question of whether the carbon footprint is decreasing or increasing when transitioning from mass to economic allocation is contingent upon the relative product mass being higher or lower than the relative product revenue. The total specific CO_2eq for lead, copper, and gold (excerpt) mined at a Boliden mine (e.g. Kevitsa) and smelted at a Boliden smelter (e.g. Harjavalta) are as shown in table 1. The prices used are the ones that Boliden uses internally for their calculations [25]. More details on the calculation, containing all the metal products by Boliden, can be found in supplement I.

According to ISO 14044, the first step to avoid allocation is to subdivide the process into more granular components. On a first level, the O-LCA could be divided into different sites, i.e. mines, but this does not solve allocation, as each mine produces more than one product. Therefore, the subdivision needs to be even more detailed, looking at the process level within the mine sites. Figure 2 provides a schematic representation of subdivision on a process level, applied to the case study examined in this paper.

From the figure it can be seen that copper exits the system at an earlier stage of the product system, thereby avoiding the additional environmental impacts associated with subsequent steps in the production process, such as electrowinning for gold, silver, and PGMs.

However, despite this subdivision, allocation remains necessary in the context of copper–gold mining. This is a common situation in most LCAs within the metals and mining industry, as metals are often inseparable in various processes [6].

An additional benefit—or even a consequence—of subdivision is that the product system and its processes are understood in greater detail. The results of the subdivided system are presented in section 3.4.

3.2. System expansion

The Kevitsa mine, combined with the Harjavalta smelter and Pori anode slime refinery, serves as a prime example in this study. These facilities collectively produce 19 kt of copper, 10 kt of nickel, 640 t of cobalt, 1.5 t of platinum, 1.1 t of palladium, and 650 kg of gold [17 suppl. VII.V.]. In this context, expanding the system to include all these functions does not yield meaningful results, as the outputs are so specific to this mine that they would result in incomparable figures. This issue is prevalent across many mining operations, where each orebody and mine are unique in terms of product yield and composition. Unlike other production systems—such as those involving the co-production of chlorine and hydrogen—where product relationships are relatively consistent across different sites, mining operations are highly site-specific. The German cost accountant Paul Riebel argues that the cause lies in an entrepreneurial decision—such as the operation of a specific mine—and the effect is the resulting (co-) production with its associated combined cost structure [30]. He insisted on considering this structure as a whole rather than dividing it further, thus conceptualizing 'product baskets'. Riebel notes that all the allocation methods dividing the costs (environmental impacts) among the benefits may not accurately reflect the cause-and-effect, or in physics often called action-reaction, relationship between products and their environmental impacts. In economic terms, the environmental impacts (effects) occur during production, whereas the products (causes) are realized post-production [30]. This temporal discrepancy challenges the appropriateness of economic allocation, as it suggests that the effects precede the causes. Riebel further argues that the terms 'means' (impact) to an 'end' (product) would be better fitting.

In cases where system expansion by simply including the whole product basket in the functional unit is impractical, LCA practitioners typically adopt alternative strategies.

Table 1. Climate impacts for gold and copper on a company or factory level for Boliden; Prices according to Boliden 2024 [25].

Metal	Price	Allocation (mass)	Allocation (economic)
Unit:	(USD/kg)	($kg\ CO_2eq\ kg^{-1}$ metal)	
Lead	2	1.1	0.47
Copper	7.8	1.1	1.8
Gold	45×10^3	1.1	10×10^3

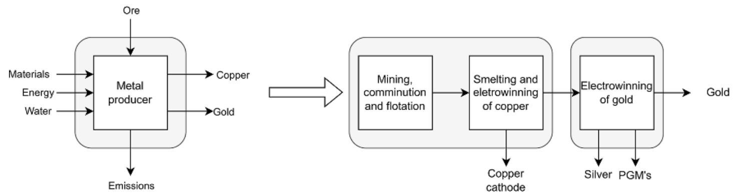

Figure 2. ISO 14044, step 1 (a) subdivision.

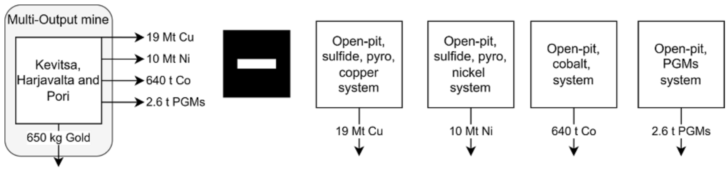

Figure 3. Solving the multi-functionality of a system by substitution.

One common approach in comparative LCA is to expand an alternative system of multiple products or to substitute certain products using alternative mono-output systems in such a way that the product weights in each product basket of the systems in comparison are the same. This method is often referred to as system expansion and substitution by LCA practitioners, which can easily be confused with step 1(b) of ISO 14044:2006, that does not explicitly talk about using alternative mono-output-systems to make the functional units more comparable [31]. For the case study here, this would involve substituting the production of palladium, platinum, nickel, cobalt, and copper in order to isolate the environmental impact of gold alone. However, this approach necessitates the use of mono-output systems; otherwise, the allocation problem re-emerges within the substituted models. In the metals and mining sector, this is frequently not feasible, as many products are not produced by mono-output mines [5]. Additionally, this approach is highly resource-intensive, as it would require detailed LCA data from five different mono-output mines to address our case.

The approach of system expansion and substitution has been subject to criticism, with some researchers arguing that it is merely a specific form of allocation rather than a true avoidance of allocation as intended by standards like ISO [15]. Essentially, this method shifts the issue from selecting appropriate allocation factors to the challenge of choosing suitable equivalence processes. Figure 3 provides a schematic representation of this approach as applied to the case study in this research.

Given the availability of the comprehensive databases SKARN, including CO_2eq for different mines with different product combinations, it was tested whether it might be practical to use substitution. However, an extensive review of the assets in the SKARN database reveals that it is not possible to identify mono-output mines for platinum and palladium—even when considering platinum and palladium together. Therefore, in the context of this study, system expansion and substitution do not adequately address the issue of multifunctionality.

3.3. Physical allocation

According to ISO 14044, if allocation cannot be avoided using step 1, then physical partitioning should be employed. This involves identifying physical relationships that represent changes in inputs and outputs. A well-known example of this approach is a waste incineration plant, where some emissions are directly caused by specific types of waste [21]. This method is often referred to as the '*polluter pays*' or '*cause-and effect*' principle [32].

Table 2. Climate impacts for gold and copper allocated by mass and revenue (economic) for the case study Kevitsa; Prices according to Boliden 2024 [25].

Metal	Price	Allocation (mass)	Allocation (economic)
Unit:	(USD/kg)	kg CO_2eq kg^{-1} metal	
Copper	7.8	8.1	3.6
Gold	45×10^3	8.9	26×10^3

In the context of the metal production system used as a case study here, it is not feasible to precisely attribute environmental impacts to specific metals, as the environmental impacts are caused by extracting the ores and are hence independent of the specific metals within the ore. This challenge is common among multi-output mines; for example, it is difficult to partition emissions resulting from blasting or the energy required for rock crushing, which affects all metals simultaneously.

3.4. Other relationships like mass or economic value

The final step, according to ISO 14044, if both step 1 and step 2 are not feasible, is to employ alternative relationships. The ISO standard cites economic allocation as one such example. Another prominent method, particularly in the metals and mining sector, is allocation based on mass or weight percentages of the products. Note that the latter is often confused with physical allocation falling under step two. According to Lai *et al,* these two methods—economic allocation and mass-based allocation—are the most commonly used approaches for allocating environmental impacts in LCAs of metallic products in the mining industry [5].

Table 2 shows environmental impacts for this study's copper–gold system, including scope 3 for the exemplary impact category of climate change.

When employing mass-based allocation, both gold and copper exhibit similar results, with CO_2eq emissions ranging between 8 and 9 kg per kg of metal. This method involves allocating the total emissions of a product system based on the mass percentage of each product and subsequently dividing by the specific product weights. Essentially, the specific emission per product weight for each product is equivalent to distributing the total emissions across the total product weight [23]. In this study, the observed divergence of 8.1 kg CO_2eq kg^{-1} Cu and 8.9 kg CO_2eq kg^{-1} Au can be attributed to the process described in section 3.1, where copper exits the product system at an earlier stage than gold.

However, this approach is problematic because the allocation of environmental impacts based on mass does not account for the fact that raw materials and associated environmental impacts often do not scale linearly with the mass of individual products but rather occur in conjunction.

Additionally, pure mass allocation does not address the issue of obsolescence: if a product becomes obsolete due to shifting market demands or technological advancements, it may be considered waste and thus should not bear any environmental burdens. For instance, the demand for cadmium, a by-product of zinc mining, declined due to environmental concerns since the 1960s and is now beginning to gain more popularity again in photovoltaic and battery technology, as noted in the keynote for the 2024 EcoBalance by Gavin Mudd [33]. Or for lead, another by-product of zinc mining, it is projected that demand will decrease significantly [34]. In such a scenario, would a zinc–lead mine continue to produce lead, and should any environmental impacts be allocated to lead production?

The system under investigation emits approximately 250 kt CO_2eq to produce 19 kt of copper, 10 kt of nickel, 640 t of cobalt, 1.5 t of platinum, 1.1 t of palladium, and 650 kg of gold. Within this system, copper is allocated the majority of the environmental burdens, accounting for 63% of the total, while gold is allocated only 0.0023% (mass allocation). This results in an emission of approximately 5800 kg CO_2eq for the production of 650 kg of gold. In contrast, the arithmetic mean for mono-output gold mines in the SKARN database (Q4 2023, reference year 2020) is 33 000 kg CO_2eq per kg of gold ($n = 128$). For 650 kg of gold, this equates to 21 kt CO_2eq. The significant discrepancy arises because, in multi-output systems such as the Kevitsa mine, the majority of the environmental impacts are allocated to copper, while in mono-output gold mines, all impacts are attributed solely to gold. Consequently, the Kevitsa production system, which generates additional metals such as copper, nickel, cobalt, and PGMs, exhibits a lower environmental impact per unit of gold produced. However, it remains uncertain whether this allocation reflects the true environmental impact of gold production.

Copper and gold exhibit a price differential of approximately 8 500 times. This raises several questions: Is gold being mined solely because of its mass, its abundance, or primarily because of its high price? At the Kevitsa mine, the principal mineral is pyrrhotite, which contains approximately 60%–65% iron. However, this iron is not included in Kevitsa's product portfolio, despite its substantial production volume. The reason for this exclusion is economic: the iron is not sold due to its lower value. This example illustrates, similar to the example of cadmium or lead becoming obsolete, that even in approaches where allocation is based solely on mass, without considering economic factors, the prices and economic value of the products still play a significant role. This leads to a fundamental question previously discussed in the context of mass allocation and obsolescence of products: Should the allocation be based on the outputs that can 'potentially' be utilized (e.g. due to their physical or chemical properties), or should it be based only on those that are actually used? The unwanted in- and outputs (e.g. burden) are always allocated to the wanted in- and outputs (e.g. benefit). The benefit in an economic system, which is the common framework when discussing mining and LCA, cannot always be measured by physical values, but rather with willingness to pay or, rather the market price.

This issue cannot be resolved 'objectively,' as it invariably relies on subjective evaluations of the products derived from the process. In natural systems, the geological formation of rocks and minerals results in a bundle of products generated as a unified whole. However, the 'Homo technicus' approach involves segmenting this system into subsystems and analyzing each subsystem individually. This segmentation introduces the allocation problem [21].

For example, in the Pueblo Viejo mine in the Dominican Republic, copper, silver, and gold are produced with a weight distribution of 85% copper, 13% silver, and 2% gold [35]. According to the allocation methods discussed, copper would bear the majority of the costs and environmental burdens associated with the Pueblo Viejo mine. This allocation approach, however, conflicts with the primary objective of the mining operation, which is to extract gold. Gold is the primary value-adding product and offers the greatest economic benefit. This is evident in the market valuation, where gold constitutes 94% of the total value, while silver accounts for 6% and copper contributes less than 1%.

An alternative allocation method that considers prices could be beneficial. In business economics, this approach is known as the '*ability-to-bear*' *principle* [32]. According to this principle, costs (or expenses) are distributed based on the value assigned to cost centers that, due to their market strength, are capable of 'absorbing' these costs.

Applying this principle to the Kevitsa mine, out of the total 250 000 tons of CO_2eq emissions associated with the production of all metals, approximately 28% would be allocated to copper (the second highest after nickel, which receives 37%), and around 6.9% would be attributed to gold. Consequently, this method significantly increases the specific impact for gold while only marginally reducing the specific impact for copper (see table 2).

From supplement II, it can be seen that based on rough estimations without precious metals Kevitsa, would have only been profitable in 2021 and 2022 (last row, last two columns from the left). Therefore, one could argue that for Kevitsa, the precious metals are not by-products but co-products [36]. The driver of the process is to make a profit based on the economic values of the products, which might not be achieved without the by-products [37].

Frischknecht argues that 'if economic and environmental aspects influence consumer choices, economic and environmental aspects should influence the determination of allocation factors for consumer goods as well' [15]. This perspective takes into account, the audience and the aims of LCAs by industry.

One often-said criticism of economic allocation is the fluctuating market prices affecting the validity and credibility of LCA results [14, 38]. The effect of fluctuating prices was analyzed with the annual, nominal prices from the World Bank's Pink Sheet [39]. Figure 4 shows the copper and gold prices as well as the copper-gold ratio based on the annual nominal prices. The graph below, figure 5, shows the same, but with a ten-year moving average applied as recommended by PE INTERNATIONAL [12]. This smoothing technique helps to 'control for price volatility that may occur in a single year' [13].

The copper-to-gold ratio is computed by dividing the market price per pound of copper by the market price per troy ounce of gold. This ratio is utilized by many economists as an indicator of various economic conditions [40]. In the context of LCA, this ratio is of interest as it provides insight into the potential uncertainty introduced into LCA results due to price fluctuations. Figures 4 (annual) and 5 (mov. avg.) show that the copper-to-gold ratio varies between approximately 70% and 40%, respectively. Hypothetically, if the production processes and associated environmental burdens of a mine remain constant over time, this variation suggests that LCA results could be subject to fluctuations of around 40% (based on the ten-year moving average).

Guinée *et al* counter the argument of price volatility by saying that the amounts of co-products produced in a multi-functional process will fluctuate per year, as will the prices of the products [37]. It was tried to check this statement, exemplary for the Grasberg copper–gold mine, based on the production figures for the Freeport Indonesia project by the annual reports from Freeport-McMoRan (2004–2024) [41]. It was found that the copper–gold production ratio fluctuates up to 60% for the time from 2000 to 2024, mainly influenced by the variance in gold production (relative standard deviation, RSD: 44%). Meanwhile, the variance of the amount of ore milled was rather low (RSD: 22%), indicating that process inputs like energy or explosives and thus the associated environmental impacts are also probably less fluctuating. It is

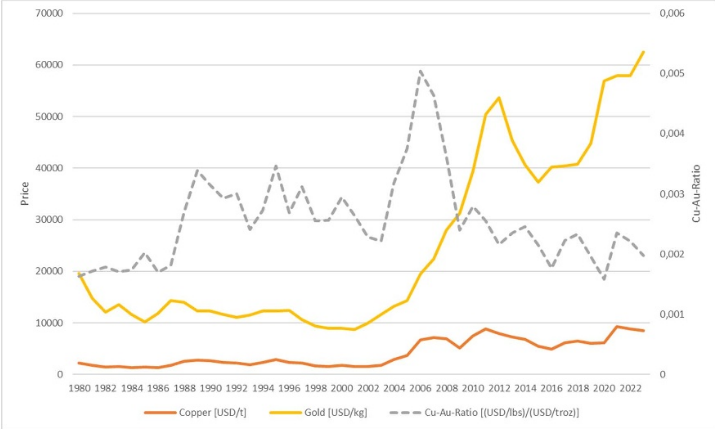

Figure 4. Copper and gold price as well as copper–gold-ratio from 1980 till 2023 (annual prices).

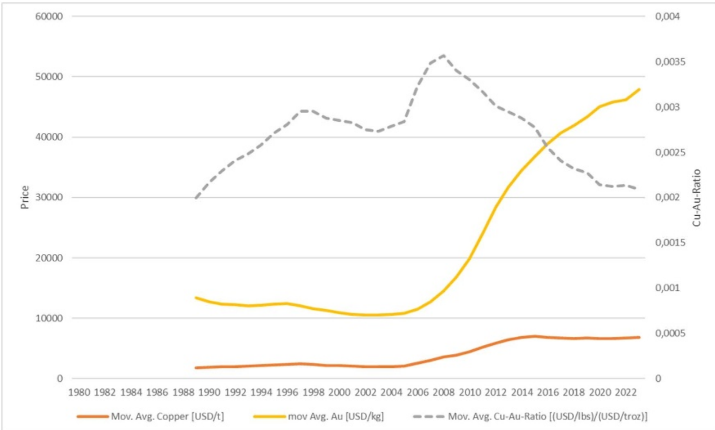

Figure 5. Copper and gold price as well as copper–gold-ratio from 1980 till 2023 (10 year mov. Avg.).

important to note that price fluctuations may be more pronounced for metals primarily used in industrial applications, such as copper, compared to those predominantly used as financial assets, like gold [40]. Gold is often described as a 'safe haven' asset [42], meaning its price tends to rise during economic crises as investors seek stability beyond currencies, banks, or stock markets [43]. In contrast, copper, being primarily an industrial commodity rather than an investment asset, may exhibit different price behavior during economic downturns.

It is important not to forget that only looking at the change of prices, assuming, that they do not influence the production itself, is not very realistic. Maximizing the output of products with high prices can influence physical flows like energy or mass consumption [14]. In mining, declining gold prices can lead to the suspension or closure of specific sections or entire mines [44]. There are examples, including in South Africa, where closed mines are reopened because of rising gold prices. As stated by Laurence *et al* 'gold mines never die; they just rest for a while' [45]. This is also in line with Huppes, who argues, that the value created causes the process, and if no value is created, then the process will stop and thus no environmental impacts will be created [16].

3.5. Process-specific allocation

As outlined in the introduction, the SKARN database employs an allocation method referred to as 'process-specific allocation'. In this approach, specific allocation rules are applied to one or more distinct processes within the production system. For instance, in the SKARN database, the environmental impacts associated with the copper smelting process are exclusively attributed to the primary metal present in the concentrate.

The results in table 3 indicate that switching from process-specific allocation to economic allocation results in a significant increase in the calculated CO_2eq for gold production, with an increase of more than

Table 3. Climate impacts of gold and copper for different allocation methods in the SKARN database for Cu–Au-mines only.

Metal	Process specific allocation	Allocation (mass)	Allocation (economic)
Unit:		($kg\ CO_2eq\ kg^{-1}$ metal)	
Copper	5.1	8.4	4.2
Gold	28×10^3	8.4	39×10^3

33%. In contrast, this change leads to a more modest decrease of about 15% in the CO_2eq for copper production (supplement III).

This allocation method by SKARN avoids categorizing copper–gold mining projects as outliers with disproportionately high environmental impacts within the gold production database. By attributing the smelting processes predominantly to copper, rather than gold, the calculated environmental burden for gold is reduced, thereby aligning these projects more closely with the most common gold production process, cyanidation, which do not involve smelting [46, 47]. If only the Cu–Au mines with copper as their primary metal are used, the carbon footprints would be ≈33 000 kg $CO_2eq\ kg^{-1}$ Au using the process-specific allocation and ≈47 000 kg $CO_2eq\ kg^{-1}$ Au using economic allocation.

Looking through an industry lens, this allocation approach might be rational. Through the gold industry lens, attributing the smelting process primarily to copper minimizes the environmental impact assigned to gold production, thereby preventing copper–gold mines from skewing the data in the gold production database. Since smelting is not a standard process in gold production, its exclusion from the gold lifecycle reduces the apparent CO_2eq burden. Conversely, through the copper industry lens, where smelting is a common and essential process, it might seem appropriate to assign the environmental impacts of smelting to copper output. This ensures that the environmental burden reflects the actual processes involved in copper production.

4. Conclusion

The purpose of the current study was to discuss the challenges of the different allocation methods in LCA for multi-output systems using CO_2eq of mining as a prime example.

This study has identified that subdivision does not resolve the allocation problem in LCA for the metals and mining industry. Breaking down the product system into smaller units or more granular steps does not effectively address multi-functionality, as metals occur together in many process steps as they are trapped together inside the ore or the WEEE. It is still always recommended to subdivide the system as far as possible, as some process steps may indeed not involve all metals and do therefore affect the allocation. Additionally, as the LCA practitioner subdivides the system, more and more knowledge of the system is gained, and the LCA gets more detailed.

System expansion is not particularly useful due to the heterogeneity of mines, making it difficult to derive meaningful results for the product basket from the LCA. Mines are too different in their operations and outputs to allow for a representative and coherent product basket as a functional unit, rendering the outcomes of such a system expansion less meaningful. The results are simply not comparable.

In LCAs the system expansion described in ISO 14044 is often extended by adding or subtracting mono-output processes of other product systems to or from the system under investigation in such a way as to have similar functional units. This is inherently complex, as it requires a comprehensive LCA for each by-product based on a mono-output system. This poses a practical challenge in the metals and mining sector since mono-output mines or even recycling facilities do not exist for several metals. Moreover, the arbitrary nature of choosing an allocation method is merely replaced by arbitrariness in selecting substitution systems.

In metals and mining, physical allocation based on the cause-and-effect principle is difficult to achieve because emissions cannot be precisely attributed and quantified for a specific product within the orebody or WEEE. It is frequently misunderstood that distributing environmental impacts by the percentage of physical parameters like mass or exergy to the products would be a form of physical allocation, but this is not a cause-and-effect relationship as described in the ISO.

Only the third step, which ISO 14044:2021-02 considers the last resort, is genuinely applicable in the metals and mining sector. Namely, the step of finding distribution keys to allocate the impacts to the products.

Allocating by weight percentage is unsuitable for a metal like gold, of such high economic value. Ores inherently contain more metals than are ultimately produced and sold, dictated by which metals are economically viable to extract. In the Kevitsa case study used within the presented paper, e.g. iron is the most abundant metal in the ore, but it is not a product of the mine. Consequently, even mass-based allocation implies an inherent economic value.

Economic allocation is frequently criticized due to price volatility, which is particularly significant for product pairs such as gold (as an investment) and copper (industrial use). The present paper shows that these influences can lead to fluctuation in environmental impacts of around 50%. Conversely, it was shown through the example of the Grasberg mine that the fluctuations in the annual production ratio between copper and gold can be comparable to those of prices.

A mine exists primarily to make economic profit. The costs of the products can only be borne by the metals with high enough market prices. But what if the market decides that a product is not needed anymore, the prices drop close to zero, and the product becomes obsolete? The question is, should the allocation be based on the outputs that can 'potentially' be utilized (e.g. due to their physical or chemical properties), or should it be based only on those that are actually used? Despite the shortcomings, we still consider economic allocation to be the best method for cases where several products with great product price variations exist.

Another way of allocating the costs, or, in the case of LCA, environmental impacts, might come from the mathematical scholar of cooperative game theory. The Shapley value is such a method that could help to fairly distribute the environmental impacts among the products. These mathematical models have already been discussed in the context of LCA [48–50], but there is no detailed study on using Shapley values for a fair distribution of multi-output allocation. Future studies should address this topic in the field of metals and mining.

The ISO standard does not address the question of benefits. In our modern world, benefits are determined primarily by market price today and, since the rise of neoliberalism, more than ever before. Metallurgists, mining engineers, or simply any natural scientists who have meticulously gathered and calculated precise technical data for their LCA models may be dissatisfied with allocation based on market prices. However, this perspective overlooks the realities of our economic systems. The ISO standard must recognize this and be adapted accordingly, not only by incorporating LCA experts from the natural sciences or standardization experts from engineering but also by including perspectives from business administration, economics, and the social sciences.

Accurate, transparent, and standardized LCA results are essential for informing policy and practice because they provide a reliable basis for decision-making. Policymakers and practitioners rely on LCA to evaluate environmental impacts, compare alternatives, and develop strategies for sustainable development. The high influence of allocation methods on the results, in combination with the lax rules for choosing the allocation methods, create a potential loophole that calls for better standardization. We call for clearer rules to allocate environmental impacts while implementing case differentiation instead of rigid hierarchies. Such measures can enhance transparency, consistency, and comparability across studies. A future focus on the benefits of product systems in the standardization of selecting allocation methods could be a way forward to ensure that LCA results best reflect the real world.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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5.3. Paper III: Mercury and CO2 emissions from artisanal gold mining in Brazilian Amazon rainforest.

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Mercury and CO_2 emissions from artisanal gold mining in Brazilian Amazon rainforest

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The Tapajós River basin in Brazil is one of the world's regions most affected by artisanal gold mining (ASGM), which is responsible for the release of mercury and high energy consumption. Mercury, mixed with gold-containing materials and then released through heating to extract the gold, can be recovered using a simple distillation device called a retort. Use of these tools has now become standard. In a comprehensive study, we investigated the use of mercury and energy at 47 mining sites in the Tapajós River basin. These included numerous mines that were operated informally or in some cases even illegally and are therefore not accessible to outsiders. Our survey shows that 1.7 kg of mercury are used per kg of gold extracted, of which only about 0.19 kg of mercury is released into the environment when retorts are used. Overall, this means an annual release of at least ≈2.5 tonnes of mercury in the region, even when retorts are used. We also find that ASGM contributes to climate change through energy consumption responsible for the release of about 16,000 kg of CO_2 equivalent per kilogram of gold. This means that even artisanal gold mining, which uses retorts, has a major environmental impact.

Gold is a commodity that has captivated the human imagination for thousands of years. Demand remains undiminished, with about 4,000 to 5,000 metric tons being produced every year worldwide. About one-third of this production is recovered from recycling (2021: 1,136 t); the rest is newly mined (2021: 3,581 t) (ref. 1). But the mining process is associated with a high environmental impact. Due to gold's low content in rock, large amounts of energy are required. Major concerns arise due to environmental damage by chemicals, social issues and regulatory and governance issues. Recycling gold could substantially reduce environmental impact[2], especially because large quantities of gold are in circulation. It is estimated that the anthropogenic gold stock is about 200,000 tons[1]. But the search for gold goes on because for many impoverished people, digging for gold is synonymous with digging for money. Artisanal and small-scale gold mining (ASGM) supplies about 700 tons every year[1] under particularly problematic conditions. Impacts such as deforestation, the release of toxic chemicals such as mercury and the high impact on climate change associated with fossil energy consumption cannot be ignored. In ASGM, problems are exacerbated by sometimes adverse working conditions and regulatory and governance problems caused by unregulated and sometimes illegal mines.

In numerous field surveys and visits to a high number of ASGM sites in Brazil, mainly in the period of 2018–2022, we investigated mercury use and impact on climate change, providing valuable empirical data for further scientific discussion. Several points make Brazil an interesting object of study. The distribution of ASGM based on the population involved in mining[3,4] shows that with the exception of China, ASGM hotspots are located in tropical rainforests. Brazil is the country with the highest ASGM population in the Amazon rainforest. The world's largest ASGM district, the Tapajós River basin, which is where we conducted our fieldwork, is also in Brazil[5]. Especially in this climate zone, economic activities such as ASGM, the protection of nature and biodiversity and the rights of indigenous peoples clash, as in hardly any other place on earth. ASGM thus represents a prime example of conflicting sustainability goals.

The use of mercury still plays a decisive role in ASGM, although its harmful effects on health and the environment are well known.

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Fig. 1 | The four main mining types of ASGM in the Tapajós. Photographs show (clockwise from top left) underground mining of primary deposits (*filão*), open pit mining of primary deposits (*filão*), open pit mining (*baixão*) of secondary deposits and dredge mining (*draga*) of secondary deposits.

ASGM in Brazil, which is often in remote areas where the government is unable to enforce the law, is an illustrative example of this. In 2017, the United Nations Minamata Convention on Mercury came into force with ratification by around 140 countries (including Brazil). ASGM is one important issue in the convention, with article 7 requiring countries to draft National Action Plans (NAPs) for handling and reducing mercury usage in ASGM[6–8]. But implementation has been slow as gold from ASGM is an economic factor and mercury still plays an important role here. Since the 1990s, attempts have been made to recover mercury through simple distillation devices, called retorts, and thus reduce its release into the environment[9]. But it is unknown how effective this method is. Additionally, in Brazil, ASGM is being mechanized through the use of excavators, which raises the question how this affects the carbon footprint of gold[10].

Artisanal gold mining is prohibited in certain areas of the Brazilian rainforest, for example, in *Reservas Indígenas* and *Parque National*[11]. In these areas, ASGM is illegal and punishable by law. Outside these areas, mining is allowed with a permit. This involves registration at the national mining office (Agência Nacional de Mineração) and filing an environmental impact assessment (*licenciamento ambiental*) issued by the federal states[12]. This is a highly bureaucratic process, and as a result, few miners (garimpeiros) have the complete permit. However, they have the possibility to obtain a permit for mineral exploration with prospect mining (*pesquisa mineral com lavra experimental*) for a limited time, which is then used to mine gold. Although this practice is not illegal, it is in an irregular grey area. There is also illegal gold mining, in which the gold is laundered through legal mining operations that produce no or only small quantities of gold[13]. In addition to deficiencies in the law, there are virtually no official controls in the vast rainforest, apart from a few spectacular actions by the environmental authorities. As a result, most gold mines are informal operations, making it difficult to visit these mines, to gain trust and to conduct surveys. For this study, we visited a large number of both illegal and informal mines and exemplary licensed mines, which is a key feature of this study. A complete ban on gold mining in the Brazilian rainforest would fail as it would be impossible for the state to enforce and would only push gold miners further into remote areas where the potential for conflict with indigenous people would increase. On the other hand, greater formalization—that is, simpler and faster authorization of gold mining accompanied by stronger monitoring—would be a first step towards improving mining conditions.

This is particularly true for the handling of mercury in the mines. Contrary to many opinions, the purchase and use of mercury is allowed in Brazil under certain conditions, and mercury use in ASGM is still standard practice. There is a lack of clear specifications and government monitoring[14]. Although there was a strict government regulation in 1989 that required ASGM to register mercury recovery facilities[15], this was withdrawn in 2015[16]. Here, too, greater formalization of gold mining could substantially improve mining conditions. This would also help Brazil to comply with the spirit and the letter of the Minamata Convention, that is, to substantially reduce the use of mercury. But Brazil has not even fulfilled the formal requirements of the Minamata Convention, which it signed in 2017, and is now more than two years behind in submitting its NAP to the United Nations[17,18].

A unique feature in the Tapajós region is that ASGM uses several different mining methods, which were thus able to be investigated in this study: mining of secondary deposits on land (*baixão*) and by dredges (*dragas*) and mining of primary deposits underground and in open pits (*filão*) (Fig. 1). In so-called primary deposits, gold is embedded in rock veins. When primary gold deposits are eroded and flushed out of the rock as fine gold dust or as small grains, they are called secondary deposits. Baixão is the most common method in the region. This process uses water jets to elutriate gold-bearing soil, pumping it over sluice boxes and amalgamating the gold with mercury, a process well described in many studies[19,20]. The gold production process of the dragas is very similar to the process on land but without the need for water jetting, as the sediments from the riverbeds can be pumped over the sluice box directly[21]. A common technique for mining the filão in ASGM uses amalgamated copper plates to trap the gold in the crushed ore[22]. Sometimes the crushed ore is also leached with cyanide instead of or in combination with mercury use before cyanidation[6] on the amalgamated copper plates to extract the gold. The latter technique should be eliminated as part of the NAP of the United Nations Minamata Convention on mercury.

Social conditions in ASGM mines, deforestation rates and the effects on health of mercury in rivers and soils have been studied many times[6,23–25]. Our team published a separate article on the social aspects of the ASGM sector in the Tapajós region, for example, the absence of the state, the illegality and informality of mining operations, poor working conditions, difficult living conditions, unstable payment of wages and autonomy[26]. Much research on mercury in soils, plants, waters, fish and humans has also been done in the Brazilian Amazon rainforest since the end of the 1980s[5,19,26–28]. Studies of the specific amounts of mercury used and recovered in ASGM are, however, rare. They have small sample sizes of very few different types of mine, and

Fig. 2 | A typical retort. Photograph shows a typical retort as used in the Tapajós region.

there are problems in comparability[21]. Even less research has been done on energy intensity and the climate impact of ASGM. Studies on energy intensity, all in countries other than Brazil, mostly refer to individual mines and specific regions, and there are methodological problems in comparing the results[29–31]. The international discussion about climate change and the contribution of mining to greenhouse gas emissions is gaining importance, which was the motivation for us not only to look at mercury in ASGM but also to determine energy use.

There is still a gap in knowledge about the current extent of mercury use, retort efficiency and the carbon footprint of ASGM. The Tapajós region, which is known to produce at least 15 tons of gold per year[13], provided the opportunity to collect a larger amount of empirical data for different mining methods within a reasonable amount of time. This included mines that were inaccessible to outsiders and about which little in situ data are typically published. In our study, we were able to collect and analyse data on energy consumption, mercury use, loss and recovery from over 100 data samplings at different mines. The Tapajós region is also well suited to this research because here ASGM shows a development in mechanization that might sooner or later take place in other regions of the world. In addition, since the 1990s, there have been several programmes to train miners in the use of retorts, but there is no record of how many of ASGM sites (*garimpos*) in the region use retorts[32].

The loss and recovery of mercury in ASGM

Retorts are very simply built (Fig. 2). Using a gas burner and a distillation, the mercury is evaporated from the amalgam and recovered. The distribution, purchase and use of mercury is not prohibited in Brazil when it is licensed by a competent environmental agency, for example, the Brazilian Ministry of Environment[33,34]. The policies and regulations of ASGM in Brazil are much discussed and criticized because they are too complex, especially for garimpeiros, difficult to monitor and offer many loopholes[19,32,33,35]. On the basis of our surveys, the retorts cost about BRL 1,300 (Brazilian real), while a kilogram of mercury costs about BRL 1,400. Depending on the quality of the retort and the experience of the user, a retort can pay back its cost already after its second use. The results of the measurements of mercury loss and recovery are shown in Fig. 3. The sum of the mercury lost (blue bar), mercury recovered from squeezing the amalgam through a cloth (orange bar) and mercury recovered with the retort (grey bar) equals the total amount of mercury used. In Fig. 3, the values are scattered depending on the experience of the garimpeiros, the quality of the retorts and the geological circumstances, for example, ore grade.

The arithmetic mean of mercury used is 1.7 kg per kg of fine gold (Au). The arithmetic mean of mercury lost is around 0.19 kg per kg of Au (blue line in Fig. 3), taking place at different stages of the gold production. Spillage occurs while mixing the mercury with the gold-bearing concentrate from the carpets or while panning the mercury-concentrate mixture. This leads to metallic mercury emissions to soil and/or river water. The recently introduced practice of separate water basins for panning the gold in a closed system away from the rivers (*piscinas*) is therefore especially important. Another type of loss is leakage, when the mercury is evaporated in the retort, which results in mercury emissions to the atmosphere. Some mercury also remains in the sponge gold, which is first released after the sponge gold is sold to gold shops and formed into a doré bar. There are some indications that after the amalgam is burned for 15 to 20 minutes in a retort, the content of mercury in the sponge gold is rather low[36]. This practice differs from other countries where the amalgam is often first burned in the gold shops.

Figure 3 clearly shows that the loss of mercury is substantially lower than its use. This is a success of the use of retorts, which are able to retain at least 75% of the mercury, depending on the quality of the retort and the experience of the user. What stands out in Fig. 3 is that for the measurements on the Hg13, Hg24, Hg25 and Hg55, the total mercury loss was negative. All the four cases were on *dragas*, meaning that those four measurements recovered more mercury from the riverbed than was originally used. This is in line with results from Balzino et al.[21]. We can conclude that there is a significant amount of metallic mercury in riverbed sediment, most likely from former mining activities. The high mercury levels in sediments in rivers and lakes in the Tapajós region is a well-researched and long known phenomenon[27,28]. In 1994, Reuther already showed that much of the metallic mercury directly released from the mines persists as metallic mercury[27]. *Dragas* function as collectors of old mercury deposits, but they have other major impacts on river flora and fauna. The substantially higher value from measurement Hg34 is due to the fact that old sediments were reprocessed from abandoned *garimpo* tailings (*rejeito*) in which substantially higher gold content was expected by the garimpeiros.

In addition to the mercury recovery potential of the retorts, we also conducted a survey about the acceptance of this technology in the study area. Our results show that 88% of the *garimpos* in the area use a retort. This could be different in other regions, for example, illegal mining in indigenous territories (*reserva indigena*). But as mercury is expensive, there is an economic incentive for miners to use retorts.

Relating our results for the average loss of mercury (0.19 kg Hg kg^{-1} Au) to ASGM gold production in the state of Para, we estimated the annual mercury emissions from ASGM. ASGM gold production is reported to be 10 t Au per year and 18 t Au per year for 2019 and 2020, respectively[13]. This results in total mercury emissions of at least 5 t of mercury in the period of 2019 to 2020. By extrapolating our findings from Para on ASGM gold production to the total gold production in Brazil of 54 tons (ref. 13), we arrive at total emissions of at least 10 t of mercury in the period of 2019 to 2020. This number assumes that every *garimpo* uses a retort, which means it is an optimistic estimate.

Energy consumption by ASGM

Discussions about the environmental impact of ASGM mostly focus on mercury or deforestation, while energy consumption and its impact on climate change are often neglected. Figure 4 shows our results of 34 surveys for energy intensity per kg of fine gold (Au) of the different types of gold mining technique in the Tapajós region. Most available data were on the production of gold from secondary deposits on land with excavators. This is also the most common form of gold mining in the Tapajós region. In the figure a trend can be seen in which the energy intensity per kg of fine gold (kg diesel kg^{-1} Au) of each type of mining in

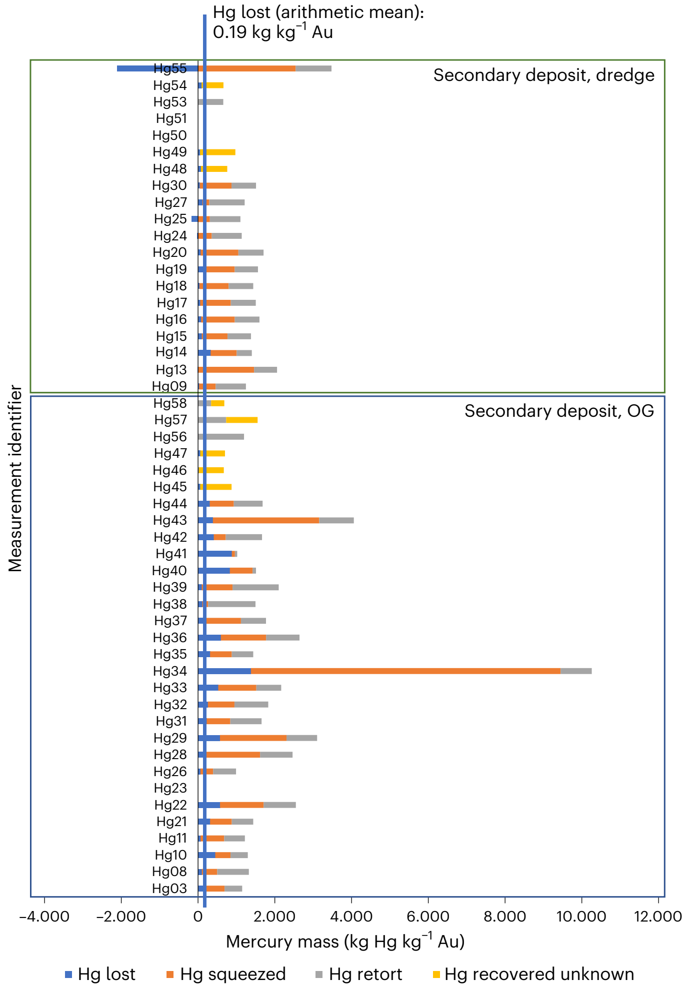

Fig. 3 | Mass balances of mercury loss and recovery. Values in kg Hg per kg of fine gold (Au) from secondary deposits mined by dredging or in overground (OG) operations in the Tapajós region (raw data in Supplementary Table 1).

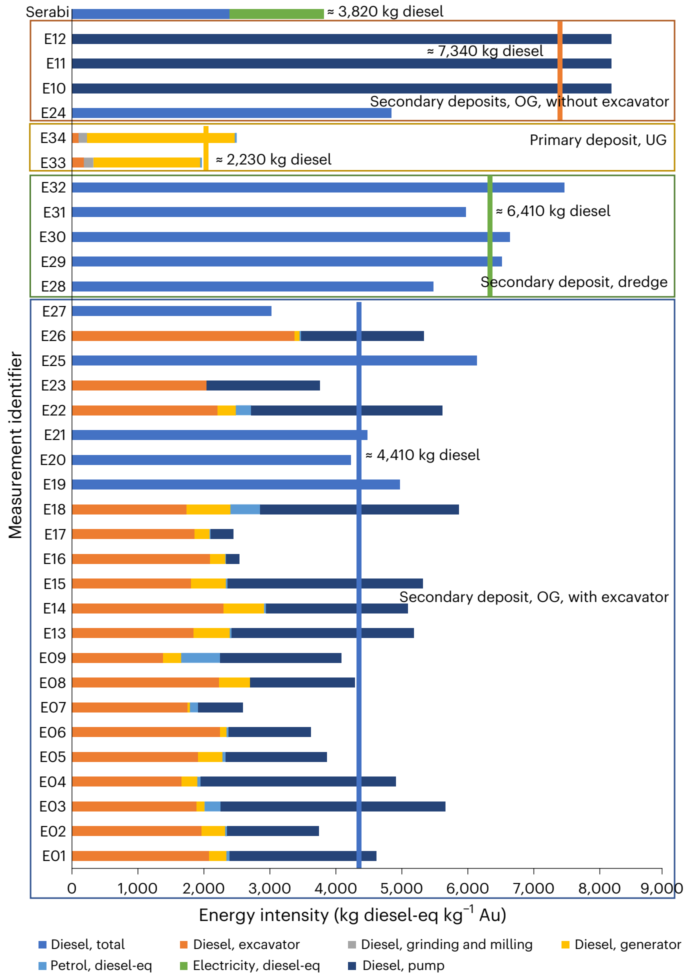

Fig. 4 | Energy consumption per kg of fine gold. Values in kg diesel equivalent (diesel-eq) per kg of fine gold for different gold production techniques in the Tapajós region (without transport). Note: OG and UG stand for overground and underground, respectively (raw data in Supplementary Table 3).

ascending order is: mining of primary deposits underground (2,230 kg diesel kg^{-1} Au), mining of secondary deposits on land with excavators (4,410 kg diesel kg^{-1} Au), mining of secondary deposits on riverbeds with dredges (6,410 kg diesel kg^{-1} Au) and mining of secondary deposits on land without excavators (7,340 kg diesel kg^{-1} Au).

A possible explanation why secondary mining with excavators has lower fuel consumption than the old method without excavators is that digging a pit with an excavator is more efficient than water jetting a pit. Mechanization also makes work for the garimpeiros easier[26] and provides the possibility to remove the fertile topsoil and backfill it later, which, however, based on our experience is rarely done. On the other hand, gold production as a whole is faster with the use of heavy machinery. This might lead to a classical rebound effect, meaning that more mines, and thus more area in the rainforest, are opened in a given time period. Additionally, the use of excavators might lead to the development of more infrastructure such as roads and airstrips in the region[37]. A possible explanation of the lowest fuel consumption for the underground mining of primary deposits is that much of the energy expended in this type of mining is from explosives (≈20 kg explosives kg^{-1} Au) and manual work. The large-scale gold mine (LSGM) Serabi (Fig. 4, bar on the top), located in the same region, has lower fuel consumption (3,820 kg diesel kg^{-1} Au) than the mining of secondary deposits on land with excavators. Serabi is also the only type of mining observed in our research that at least partly uses energy from the grid. Energy from the grid was converted to diesel equivalents (Methods) in Fig. 4 (green bar at the top).

Comparison to other gold production techniques

The carbon footprint expressed in kg carbon dioxide equivalent per kilogram fine gold (kg CO_2eq kg^{-1} Au) of each type of mining in ascending order is: mining of primary deposits underground (9,750 kg CO_2eq kg^{-1} Au), mining of secondary deposits on land with excavators (18,000 kg CO_2eq kg^{-1} Au), mining of secondary deposits on rivers with dredges (25.700 kg CO_2eq kg^{-1} Au) and mining of secondary deposits on land without excavators (29.200 kg CO_2eq kg^{-1} Au). Figure 5 compares the impact on climate change per kg of fine gold (Au) for different gold production techniques, based on our study using literature sources. Our findings show that the climate impact by ASGM is between 10 and 30 t CO_2eq kg^{-1} Au (blue area in Fig. 5). The values for ASGM are in a comparable range to more recent surveys for LSGM by the company SKARN (left bar in the green area in Fig. 5)[38].

In our study, we observed a lower energy intensity, and therefore lower climate impact, with increasing mechanization (compare the second and fourth bars in Fig. 5) because of increased process efficiency. This means that increasing mechanization can actually lead to lower climate impact. But as discussed above, this development could also lead to a rebound effect, which in turn would lead to higher climate impact for the whole ASGM system in Brazil.

The *garimpos* are in remote areas in the Amazon rainforest and all the materials (for example, diesel) have to be transported to the sites by planes, boats or cars depending on the season and location.

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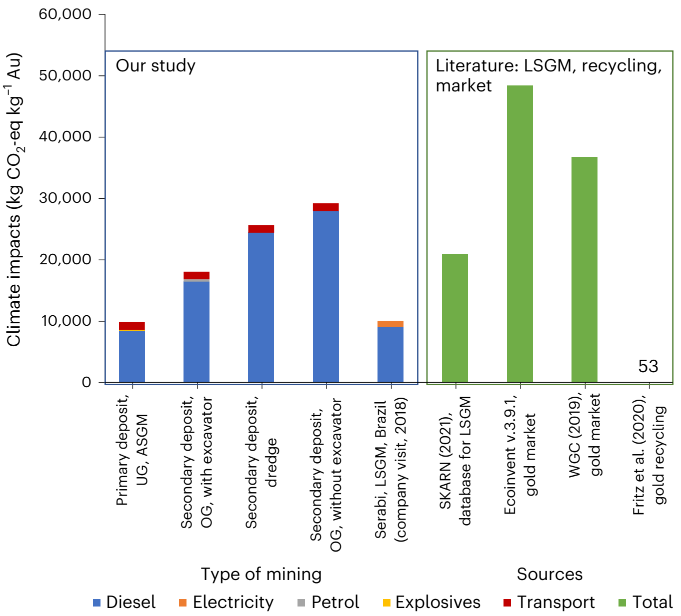

Fig. 5 | Climate impact of gold production from ASGM and LSGM. Comparison of our study and different literature values in kg CO_2 equivalent per kg of fine gold (Au) (data in Supplementary Table 4). Note: WGC stands for World Gold Council.

What stands out is that, according to our study, logistics in the *garimpos* (red section of the first four bars) only has a small contribution (1,260 kg CO_2eq kg^{-1} Au) to overall climate impact. During our expedition in 2018, we also did a two-day company visit to the LSGM site Serabi. The underground gold mine is located in a former *garimpo* in our study area. In Fig. 5 it can be seen that the climate impact by Serabi (fifth bar) is similarly low as underground ASGM (first bar) and has the lowest climate impact compared to the other gold mining techniques. This contrasts with the energy intensity values, where Serabi was comparable to mining of secondary deposits with excavators (blue area in Fig. 4). The reason for this is that Serabi utilizes about ≈40% of their energy from the grid, which in Brazil consists of only ≈10% non-renewables[39].

The climate impact of industrial gold production includes uncertainty arising from a variety of different technologies, countries, energy carriers and deposits, to name just a few sources[38,40,41]. The most accurate data currently available are probably that of SKARN, as they are based on an evaluation of almost 500 assets[38]. The value for LSGM is therefore around 21,000 kg CO_2eq kg^{-1} Au. Overall, the carbon footprints of ASGM and LSGM are comparably high.

For consumers who are not only looking for responsibly sourced gold (that is, without poor working conditions and perhaps without the use of mercury) but are also concerned about climate change, gold from modern industrial recycling is clearly the best solution with a value of 53 kg CO_2eq kg^{-1} Au (bar on the far right). Although, we can recycle only what is in circulation and the amount of gold scrap cannot satisfy market demands.

Discussion

Our research found that retorts are an effective and cheap technology for the reduction of mercury emissions. Moreover, we show that the efforts taken in the region since the 1990s to train garimpeiros in the use of retorts were successful. But our study also shows that even with the use of retorts, the level of emissions occurring is still too high. Brazil's 1989 regulation on mercury use in gold mining (which is no longer in force) specifies the use of retorts in ASGM and a mercury recovery rate of 96% (ref. 34). Our analysis shows that this rate is still far from being reached today. Therefore, our results provide an important insight for policymakers to take further steps to curb ASGM mercury emissions beyond the use of retorts.

An interesting detail was the observation that in some cases, mercury recovery was more than 100%. The reason for this is probably that the metallic mercury content in sediments is already high because gold has been mined in the region for decades with the help of mercury, and mining has also been carried out at old sites or riverbeds. It is not fully understood under what circumstances methylation of this mercury takes place, nevertheless the high mercury content in sediments means that no matter how carefully and responsibly a garimpo is using mercury, its release will continue to occur in future gold mining in the region. Thus, a greater focus on the relationship between mercury emissions and sedimentation could produce interesting findings. A large-scale survey on mercury contamination of soils in the region would also be very helpful at this point.

Additionally, we found that there has been relatively little research on ASGM impact on climate change. Our research shows that ASGM climate impact in the Tapajós varies depending on the process technology used but is overall in comparable ranges to those of LSGM. The increased use of excavators in the *garimpos* during the last 20 years could lead to a lower specific energy intensity due to an increase of efficiency. Besides its positive effects, this trend could also lead to rebound effects or acceleration of infrastructure development, for example, building roads in the rainforest. Our findings regarding the relatively high climate impact of ASGM could have significant implications for certification of environmentally responsible ASGM sites, which has focused on mercury emissions and typically not considered climate impact. This means that when gold extraction in ASGM is labelled as 'responsible', 'fair', 'sustainable' or 'green', its mining may minimize mercury loss but potentially create a non-negligible amount of CO_2 emissions. As the impact on climate change by gold mining mainly results from burning fossil energy, high investment in regenerative energies would be necessary.

A further limitation is that our results refer to the Tapajós region. In other regions, the situation may be different. However, the extensive gold mining in the Tapajós region is diverse and is indicative of how gold mining could develop in other regions of the world, especially through mechanization by machines but also through the use of simple tools such as retorts. In this respect, we consider our analysis to be relevant for ASGM in other countries as well.

Our overall conclusion is that Brazil must finally adopt its NAP of the Minamata Convention and thus fulfil the United Nations requirements on mercury. Additionally, a better and simpler formalization of ASGM permits and effective compliance monitoring are needed. But regardless of this, energy-intensive gold mining, including artisanal mining, still has a long and hard way to go to reduce its impact on the climate.

Methods

Different research methods were used to collect primary data on the consumption of diesel and petrol, mercury use and loss and the quantity of gold extracted. Primary data were gathered through measurements, interviews and questionnaires. The raw data for all our measurements can be found in the Supplementary Tables. For this study, several field trips were undertaken, mainly in the period of 2018–2022 to gather as much primary data as possible, largely through measurements of mercury and energy use and through open-ended, information-oriented interviews with complementary observations[42]. All interviewees were aware of the purpose of the interviews and agreed to it. Research expeditions were made to small villages in the Tapajós region and the cities of Santarém, Itaituba and approximately 50 mining sites. Many contacts emerged from people one member of the research team personally knew, which gave us access to sites that would otherwise be inaccessible to outsiders. Starting with known contacts, snowball sampling was used to expand the network and to avoid bias[43]. Garimpeiros and *donos* (*garimpo* managers) are key actors in the sector, and thus the survey questions were formulated to mainly target these groups. In addition, politicians, scientists, shop owners, nurses, teachers and many other groups were interviewed. These interviews were also used for a social analysis published in 2020[26].

The loss and recovery of mercury by using retorts was measured 47 times in situ and is expressed in a mass balance for different ASGM sites in the Tapajós region. This is in line with the guidance document on how to develop NAPs by the United Nations Environmental Programme project PlanetGOLD[44]. To enable comparability of results (both within the study and with other reported results), it is crucial to know the fine gold (Au) content in the different gold products. For the most part, there are two physical forms of gold products in the *garimpos*: sponge gold and doré. Sponge gold is the product retrieved by evaporating mercury from the amalgam. It is then sold to gold shops, which refine it with borax to retrieve the doré. As the sponge gold is sold by individual garimpeiros in different villages and at different times, it was not possible to determine the gold content in relation to the specific weight of sponge gold. However, we were able to gather primary data on the weight of both sponge gold and doré 12 times from different *dragas* and we determined a fine gold content of ≈88% Au (mass fraction). The fine gold content in the doré (mass fraction) was determined using primary data from ten interviewees (mainly gold shop owners) from six different towns and differs depending on the production process: mining of secondary deposits on land (*baixão*: ≈91% Au) and by gold dredges (*dragas*: ≈93% Au) and mining of primary deposits underground and in open pits (*filão*: ≈78% Au).

The use, loss and recovery of mercury and the extracted gold were analysed by 47 mass balances on site[45]. This direct measurement approach is recommended by the United Nations Global Mercury Assessment[41,46]. To determine whether retort use in the *garimpos* we visited were exceptions or the rule, we conducted an anonymous random survey on retort use with 42 interviews in different bed and breakfasts, restaurants, shops, bars and cabarets in the study area. Of the interviewees, 27 were garimpeiros and 14 were managers or owners of *garimpos*.

The mass balance approach used in this study for mercury is particularly suitable in the rudimentary conditions of the *garimpos* in the Brazilian Amazon rainforest. However, it also poses limitations as we do not know the elemental composition of the samples, but only their absolute weight. Therefore, we cannot say exactly how much mercury is lost at which specific process step, and we were unable to trace the accumulation of mercury in the environment. If the mass balances for mercury use were supplemented by a handheld X-ray fluorescence spectroscopy, it would be possible to gain more informative results. Mass balances would also need to be supplemented with soil, water and flora measurements directly at the site.

The near impossibility of doing unannounced or even undercover observations of the *garimpos* means there is an additional, uncontrolled factor that individuals may have modified an aspect of their behaviour in response to their awareness of being observed by our team (Hawthorne effect). The implications of this might be that less care is taken in gold production than we observed. But it seems very unlikely that garimpeiros work less carefully with mercury, because losing mercury that could be recovered would entail a financial loss for them.

Gold production is characterized as an energy-intensive industry with many associated impacts on climate change[40]. It is not well understood yet how the ASGM sector performs in regard to this matter. We collected data on the energy consumption of 34 different mines using different production processes. We calculated the amount of diesel used and gold produced over a fixed period of time, conducted information-oriented interviews with complementary observations and looked into the accounts of the *donos*.

From some surveys we obtained data on other energy carriers, for example, petrol for chainsaws. To unify terminology and facilitate comparability, we converted these values to their equivalent mass of diesel based on their heating value.

Additionally, we estimated the fuel demand for the logistics (mainly for transportation of fuel to the *garimpos*) needed for the production. Depending on the season and the location or the connection to the road network, the most important means of transport are boats, pickups, trucks and light aircraft. On the basis of our estimates, transport fuel consumption is around 330 kg diesel kg^{-1} Au. This consumption is not included in Fig. 4 and would be added on top of every single data point (except Serabi).

To determine logistics fuel consumption in the *garimpo*, we used satellite and georeferenced data to determine average distances between fuel stations, small towns and *garimpos*. Additionally, we had interview data for specific fuel consumption for different trucks and airplanes. From some surveys, we obtained data on other energy carriers such as kerosene or petrol. To unify terminology and facilitate comparability, we converted these to their equivalent mass of diesel based on their heating value. For the LSGM site Serabi, we also had to convert one energy carrier (electricity) to diesel equivalents. This was done using primary data gathered at the company visit in Serabi in 2018 on site-specific diesel consumption per electricity amount generated (≈0.28 l kWh^{-1}).

Finally, we estimated the associated climate change impact from our survey results on fuel consumption in the section 'Energy consumption by ASGM' and the transport and explosives of gold production from ASGM using the ecoinvent v.3.9.1 database[47].

We observed idiosyncratic and non-standard bookkeeping practices by garimpeiros, some of whom were illiterate[26]. We attempted to validate these figures by comparing them with data from the literature, machine datasheets, mass balances and natural laws. Verifiably incorrect or non-sensical values were removed. Outliers in the data were retained if there was a possible explanation for them.

Ethical statement

All our research was conducted in accordance with the statutes of the Ethics Committee for Research and Publication Projects of Pforzheim University, which is in line with the ethical requirements of the German Research Foundation (DFG). All interviewees were aware of the purpose of the interviews and agreed to it.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All raw data (anonymous) and data analysis cited in the article are provided in the Supplementary tables.

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Author contributions

Project planning: M.S., B.P.; funding: M.S.; methodology: B.F., B.P., M.S.; on-site data collection: B.P., B.F., L.d.S.T., A.C.d.S.A.; data analysis: B.F., B.P.; validation: M.S.; writing: B.F., M.S.

Competing interests

The authors declare no competing interests.

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Ecological, evolutionary & environmental sciences study design

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Study description	In our study, data on energy consumption and mercury use and recovery in the Brazilian Amazon Rainforest were collected through interviews and measurements.
Research sample	Several field trips to aproximately 50 mining sites for interviews on energy consumption. For mercury use and recovery 47 mass balances were done in the mining sites.
Sampling strategy	No sample size calculation was done, as it is very hard to gether data in the remote and irregular gold minining sites in the middle of the Amazon Rainforest. We therefore tried to just gather as much data as possible.
Data collection	Data collection was mainly done by Bernhard Peregovich (UFOPA) and Benjamin Fritz (HS PF). For energy consumption via interviews and questionaires. For mercury use and recovery through measurements (mass balance).
Timing and spatial scale	2018 - 2022
Data exclusions	Verifiably incorrect or nonsensical values were removed. Outliers in the data were retained if there was a possible explanation for them.
Reproducibility	n/a; The measurements are unique.
Randomization	Not relevant, because of the remote character of the mines, that are not open to the public, you can not be selective with you participants. Most of the times, interviewees will not tell you too much about their background in order to stay anonymous.
Blinding	n/a

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	Mainly dry season in Brazilian Amazon Rainforest with little rainfall.
Location	Our results refer to the Tapajós region.
Access & import/export	not relevant
Disturbance	Possibly disturbance with positive effects as individuals might have modified an aspect of their behavior in response to their awareness of being observed by our team (Hawthorne effect).

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Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

5.4. Paper IV: Environmental impact of high-value gold scrap recycling

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The International Journal of Life Cycle Assessment (2020) 25:1930–1941
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DATA AVAILABILITY/DATA QUALITY

Environmental impact of high-value gold scrap recycling

Benjamin Fritz[1] · Carin Aichele[1] · Mario Schmidt[1,2]

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Abstract

Purpose The gold routes satisfying the global gold supply are mining (74%), recycling of high-value gold (23%), and electronic scraps (3%). Besides its applications in the investment, jewelry, and industrial sector, gold also has a bad image. The gold production in industrial as well as artisanal and small-scale mines creates negative impacts such as resource depletion, extensive chemical use, toxic emissions, high energy consumption, and social concerns that are of great importance. On the other hand, almost all gold is recycled and has historically always been. In common life cycle assessment (LCA) databases, there is no data on recycling of high-value gold available. This article attempts to answer the question what the ecological benefits of this recycling are.

Method In this study, we were able to collect process data on the most commonly used high-value gold scrap recycling process, the aqua regia method, from several state-of-the-art German refineries. With this data, life cycle inventories were created and a life cycle model was produced to finally generate life cycle impacts of high-value gold scrap recycling.

Results This study contains the corresponding inventories and thus enables other interested parties to use these processes for their own LCA studies. The results show that high-value gold scrap recycling has a considerably lower environmental impact than electronic gold scrap recycling and mining. For example, high-value gold scrap recycling in Germany results in a cumulative energy demand (CED) of 820 MJ and a global warming potential (GWP) of 53 kg-CO_2-Eq. per kg gold. In comparison, common datasets indicate CED and GWP levels of nearly 8 GJ and 1 t-CO_2-Eq. per kg gold, respectively, for electronic scrap recycling and levels of 240 GJ and 16 t-CO_2-Eq. per kg gold, respectively, for mining.

Conclusion The results show that buying gold from precious metal recycling facilities with high technological standards and a reliable origin of the recycling material is about 300 times better than primary production.

Keywords Gold recycling · Gold refining · Gold mining · Life cycle assessment · Environmental impact · Aqua regia

1 Introduction

Gold is used in many different products, from luxury accessories and securely guarded bars to tiny amounts in electronic goods. The gold entering our market comes either from mining or from recycling. The total gold supply in 2018 was 4670 tons, of which 23% was attributed to the refining of gold-containing scraps such as jewelry or coins, 3% came from the recycling of waste electrical and electronic equipment (WEEE), and the rest was newly mined gold (Hewitt et al. 2015; GFMS 2019).

It is well known that most precious metals have major environmental impacts since large pits or deep shafts must be dug in the ground to extract relatively small amounts of the desired metals. The ore contents in gold mining range from only half a gram per ton of ore, for example, in the artisanal and small-scale mining (ASM) in Brazil to several tens of grams per ton of ore in the large industrial mines in Canada or Australia. Furthermore, chemicals such as cyanide or mercury are used for extraction. The widely quoted study by Earthworks (Septoff 2004) stated, for example, that a wedding ring produces approximately 20 tons of toxic waste. On the other hand, gold is almost perfectly recycled because of its

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value and precious metal properties. However, what are the ecological benefits of this process, and could it be that we are doing wrong to the material gold if we lump all production routes together?

The newly mined gold can further be divided into the two categories of primary and secondary deposits. Primary deposits are ores that formed during the original mineralization periods, as opposed to secondary deposits that are a result of alteration or weathering (Pohl 2005; Renner et al. 2012). Primary deposits are mined either using open pits or underground mining, while secondary deposits are mainly mined from water bodies with dredges or by washing old riverbeds using hoses (hydraulic mining) (Priester and Hentschel 1992; McQueen 2005). Today, secondary deposits are almost solely exploited by ASM, in contrast to large-scale commercial mines.

What all mines have in common is that so-called dore bars are first produced, which, in addition to gold, contain other elements such as silver or mercury. Dore bars are usually shipped to internationally recognized refineries, which cast them on site and produce high-quality (99.99% purity) bars (Eibl 2008). However, certain refineries differ from others in that these refineries refine or recycle only scraps but not dore bars.

These precious metal recycling facilities are the focus of this study, and their scrap input is further divided into three groups: high- and low-value gold scraps and sweepings. High-value gold scraps mainly consist of jewelry with some coins and bars with a high gold content. Low-value scraps are versatile in their occurrences but mainly originate from the automobile and electronic industries (World Gold Council 2018). Sweeping waste is mainly waste from jewelers like residues from polishing, clothes, floor sweepings, etc. (Ferrini 1998; Renner et al. 2012). The composition of the different gold production routes can be seen in Fig. 1.

There are several different gold refining processes. The process used depends mainly on the size of the refinery and the type of input material (George 2015). Certain processes, such as *Miller chlorination* or *Wohlwill electrolysis*, are better suited to refine primary materials from mines such as the aforementioned dore gold on a large scale (Corti 2002). Other processes, such as *aqua regia*, are better suited to refine secondary high-value gold scraps (Chmielewski et al. 1997; Sum 1991). More precisely, the aqua regia process is recommended for refining high-value (> 75% Au), non-dore scraps, since it is the fastest, simplest, and most robust process (Adams 2016).

Interestingly, in addition to its decorative use as jewelry, gold serves a dual function. First, in tiny amounts, gold satisfies various industrial needs, and second, in bars, coins, and sometimes even jewelry, gold is used as a safe investment. For gold producers, the profit generated by gold, as for any other product, is made up of the turnover less the costs. In contrast to other products, there is no need to worry about the sales and customer acquisition markets. This characteristic is the main incentive for the simple gold prospectors in the ASM sector. Metaphorically speaking, digging for gold is like digging for money. The aboveground gold stocks comprise 48% jewelry, 31% investment applications, and 21% industrial and other uses (World Gold Council 2018). With all the gold in banks and in private possession, strictly speaking, gold should not be a critical or scarce material, at least not for industrial purposes.

An established analysis method of the environmental impacts along the life cycle of products is life cycle assessment (LCA). In their study on the environmental impacts of smartphones by Ercan et al. (2016) using the LCA database ecoinvent for upstream chain activities, it was reported that gold contributes to five impact categories at 50% or higher (the largest contribution was to ecotoxicity at 60%). Similar results were reported by O'Connell and Stutz (2010) in their analysis of the product carbon footprint of a Dell laptop, stating that the main contributing component to the carbon footprint is the random-access memory (RAM), where the gold pins account for a significant share of the carbon footprint. In an extensive LCA dataset, the research by Nuss and Eckelman (2014) on the environmental impacts of the cradle-to-gate processes of 63 metals showed that gold is among the most polluting elements on a kilogram basis. As a result, the environmental impact of gold is present in product LCA studies to the extent that the ecological image of gold has also attracted the attention of public media.

On the other hand, at the global and annual scales, gold has comparatively low environmental impacts because of its rather low production volumes in contrast to those of steel or iron, for example (Nuss and Eckelman 2014; World Gold Council 2018).

Since the environmental impacts of even the smallest quantities of gold are so high in product LCAs, it is important to be able to represent the market activities in the underlying LCA databases as realistically as possible. The current database situation is as follows: the gold production datasets in ecoinvent v.3.5 contain assumptions and aggregations from one mining site to another. Mine tailing data, to give one example, is extrapolated on the basis of the mass of gold production volume from one open gold-silver mining pit in Papua New Guinea to eight other open and underground mine sites around the world. The ASM sector is still not included in any datasets today. To understand the situation in the LCA databases focusing on recycling, we recall the gold route ratios mentioned at the very beginning of this chapter with 74% of the gold coming from mines, 23% attributed to high-value gold scrap recycling, and 3% originating from WEEE recycling (Classen et al. 2009). In the ecoinvent v.2.2 market datasets, which are intended to cover the average global production of gold, a share of 30% is used for secondary production, and since only WEEE recycling data are available, it is

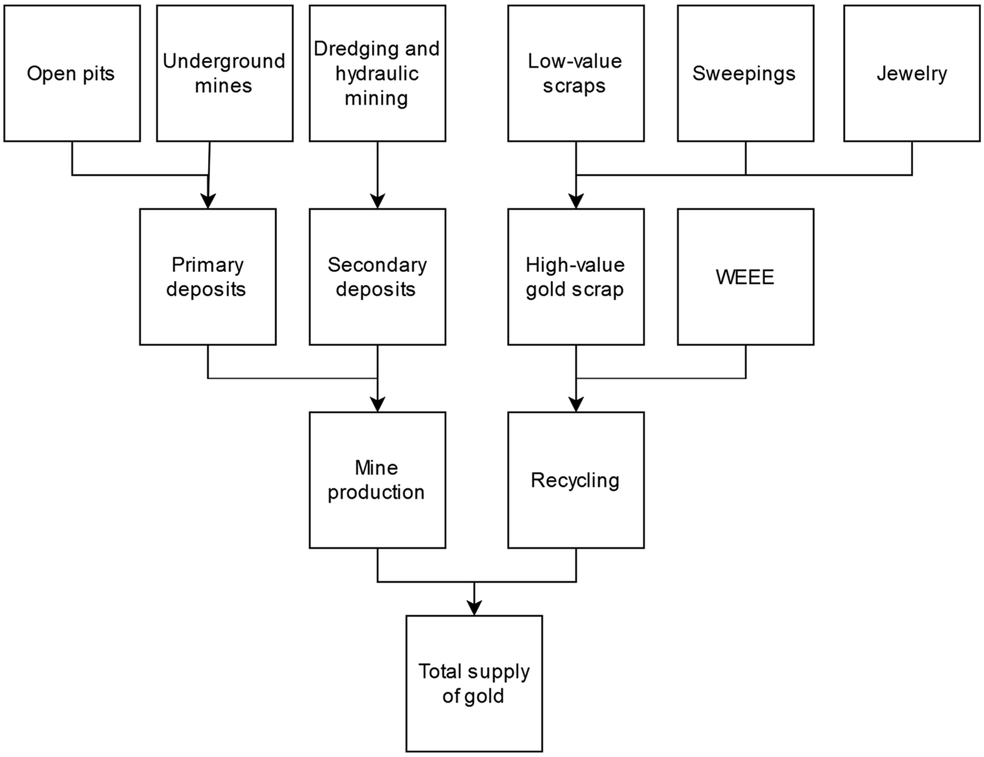


Fig. 1 Compositions of the different gold production routes of the market

assumed that the 30% share can be completely attributed to gold from WEEE recycling (Classen et al. 2009). Since WEEE recycling involves a large number of different materials with different compositions but a low content of valuable metals, high-value gold scrap recycling is therefore a less elaborate process than WEEE recycling (World Gold Council 2018). In the ecoinvent dataset v.3.4, this shortcoming is corrected by omitting the mass fraction of high-value scraps, resulting in a 99% gold share from mining and a 1% gold share from recycling, which is also not representative of the real situation. In the GaBi database (PE International 2019), the high-value gold recycling route is represented with a share of 27%, but the route is represented by a simple smelting process without refining processes, which probably does not reflect reality since refineries have more complex metallurgical processes than just smelting. An overview of how the different LCA databases represent the gold supplying routes, contrasted to what is known from market statistics, is shown in Fig. 2.

On the other hand, it is supposed that of the approximately 190,000 tons of gold mined until today, the amount of gold historically lost is approximately 2 to 15% (Butterman and Amey 1996; George 2015; GFMS 2019). This supposition is made because gold has the special characteristics that it has always been valuable, is resistant to corrosion and oxidation, and was therefore always recycled or rather reused. Gold could be considered a kind of exemplary case study for the concept of the circular economy (CE), which started forty centuries ago. However, at the same time, this study fits well in the discussion about the limits of the CE because even in the case of a high-value and noble metal, it is not possible to completely close the loop.

Until now, it has been difficult to obtain data on gold recycling processes, as the gold market as a whole tends to keep information intended for the public discreet. This study helps to better understand how effective the recycling of gold scraps into fine gold is. The study could even serve as a prime example in Germany, compared with the prominent and well-publicized stories of the WEEE recycling sites in the developing countries such as the Agbogbloshie market in Accra City, Ghana (Asante et al. 2012; UNEP et al. 2019; Ongondo et al. 2011). Furthermore, we are aiming to develop life cycle inventories for this specific process route. The question we are trying to answer for the first time is the following: how can we close the data gap in terms of the gold from precious metal recycling facilities to raise the integrity of the market activities involved in the gold supply within the LCA context?

2 Methodology

To finally examine and close the LCA data gap of this missing 23% share of the total gold supply from recycling, an extensive study was conducted on the processes commonly used for the recycling of gold scraps and how these processes work. Subsequently, for the first time primary data were gathered for the prior detected processes from a number of state-of-the-art precious metal recycling facilities in Pforzheim with a

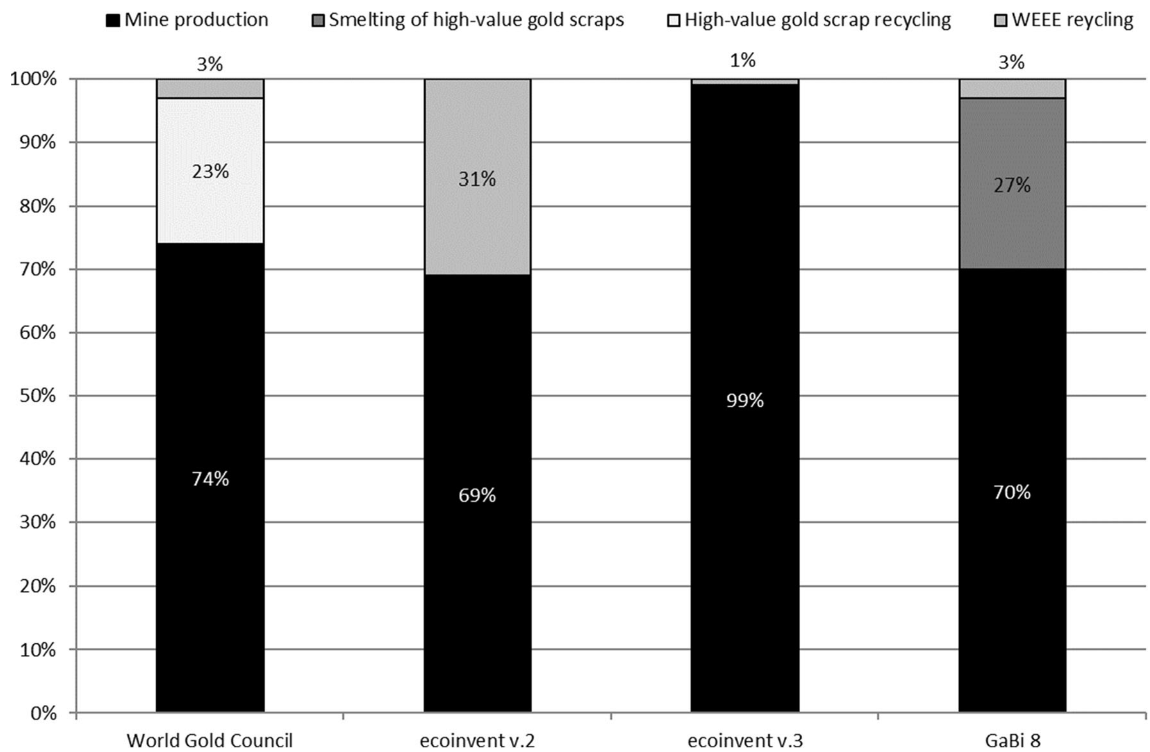


Fig. 2 Representation of the gold route shares in the different LCA datasets (private communication)

production volume of approximately 50 tons of gold per year. As the refineries under investigation are located in Germany, there are many laws and regulations that employers must follow to ensure the well-being and fair and equal treatment of employees. For reasons of confidentiality, the facilities must remain anonymous, but these facilities represent rather a best practice case for the gold scrap recycling in Germany and thus in highly industrialized countries.

To use the collected data for environmental assessments such as LCA, certain general specifications were agreed upon. The system under investigation, or in other words the foreground system, ranges from the preparation of the refinery input materials to the product output of 1 kg of 99.99% fine gold granulate. The 1 kg of 99.99% also represents the function unit (FU). The system boundary is a cradle-to-gate system. This boundary was determined because in recycling, a cut-off system model is typically used, and the other phases, such as collection or transport, are negligible (1% of the total GWP) compared with chemical processing due to the small shipment quantities (see supplement a).

Metals often occur as by-products in multi-output processes, e.g., as ore bodies in mining or as scraps in recycling containing multiple valuable fractions. As a result, the environmental impacts of these processes must be distributed among the value-adding precious metals. The most common method for solving this problem, also recommended by the DIN ISO EN 14044, is allocation by mass or monetary value. Allocation by mass means that the metal with the largest quantity is assigned the highest environmental impacts and vice versa. Allocation by monetary value means that the metal with the highest value in the process (mass times the market value) will have the highest impacts (Bruijn et al. 2004). In LCA studies on metals, the prevailing opinion is that mines are only operated because their products have a high monetary value (Tuusjärvi et al. 2012). Often mines are closed when gold prices make mining unprofitable and reopened later when the gold price rises. In the current COVID-19 pandemic, we observe this phenomenon especially in ASM, as the price of gold is high and the price of oil is low. Nevertheless, for the inventory of the in- and output flows of the high-value gold recycling process in this study, allocation was performed using both mass and economic factors. For a more detailed explanation of the allocation method, see Supplementary material b.

Different refineries recycle different qualities of scrap depending on economic and technological decisions. In practice, this condition means that there are various processes upstream of the aqua regia process to bring the different input scraps to concentrations suitable for the aqua regia process. These processes are mainly electro- and pyrometallurgic. To make this as meaningful as possible in this study, we will distinguish two different cases. Case A will represent the ceteris paribus case for the hydrometallurgical treatment of high-grade gold scrap using the aqua regia process. Case B is an extension of Case A with the abovementioned electro- and pyrometallurgic upstream processes. The ratios in case B are based on the

Table 1 Inventory for different processes with mean values gathered from various refineries in Germany (values rounded)

Input			Output		
		Process: low-value scrap preparation (amount per kg lv)			
	By mass	By monetary value		By mass	By monetary value
Low-value scraps	250 kg	250 kg	Wastewater, internal	0.3 kg	14 kg
Electricity	12 MJ	270 MJ	Gold-enriched low-value scraps (lv)	1 kg	1 kg
Nitric acid	58 g	1.1 kg			
Sulfuric acid	37 g	4.6 kg			
		Process: sweepings incineration (per kg sweepings)			
Sweepings		1.9 kg	Carbon monoxide, fossil		0.38 g
Electricity		11 MJ	Carbon dioxide, fossil		6.3 kg
Natural gas		2.5 m^3	Hydrogen chloride		0.14 g
Activated carbon		17 g	Nitrogen oxides		12 g
			Particulates, > 2.5 μm and < 10 μm		61 mg
			Sulfur dioxide		0.20 g
			Sweepings, ashes (sa)		1 kg
		Process: granulation of scraps, prepared (per kg scrap)			
High-value scraps		0.44 kg	Scraps, prepared and granulated for the aqua regia process (sg)		1 kg
Gold-enriched low-value scraps		50 g	Wastewater, internal		13 kg
Sweepings, ashes		0.51 kg			
Electricity		0.45 MJ			
Tap water		13 kg			
		Process: aqua regia (per kg Au)			
Scraps, prepared and granulated for the aqua regia process		3.3 kg	Silver, in silver chloride		0.45 kg
Electricity		45 MJ	Palladium, in solution		59 g
Hydrochloric acid		3.4 kg	Platinum, in solution		44 g
Hydrogen peroxide		6.4 kg	Non-valuable fraction		1.7 kg
Nitric acid		0.7 kg	Wastewater, internal		24 kg
Sulfur dioxide		0.93 kg	Gold dust		1 kg
Tap water		13 kg			
		Process: granulation of gold dust for sale (per kg Au)			
Gold dust		1 kg	Gold		1 kg
Electricity		1.5 MJ	Wastewater, internal		13 kg
Tap water		13 kg			
		Process: wastewater (per kg wastewater)			
Wastewater, internal		1.1 kg	Carbon dioxide		38 g
Sodium hydroxide		5.6 g	Wastewater, river disposal (ww)		1 kg
Quicklime		45 g	Hydroxide sludge		180 g
Natural gas		20 l			
Electricity		0.39 MJ			

mean values of the primary company data as we witnessed during the on-site visits in this study. Their quantities of low- and high-value scraps and sweepings are given in Table 1. It is important to note that the inventory for the preparation of low-value scraps condenses several different processes for the different scrap input qualities for reasons of simplicity. The two cases A and B are shown in the schematic diagram of the aqua regia process as used in this article in Fig. 3.

The first step is to prepare the input for hydrometallurgical refining with aqua regia to guarantee a mixture ratio that is suitable for the aqua regia treatment. The preparation of low-value scraps involves many different types of electrolysis processes, depending on the different qualities of the input material and the technologies available in the refinery. The preparation of sweepings entails the incineration of the inputs, which burns off all the organic material.

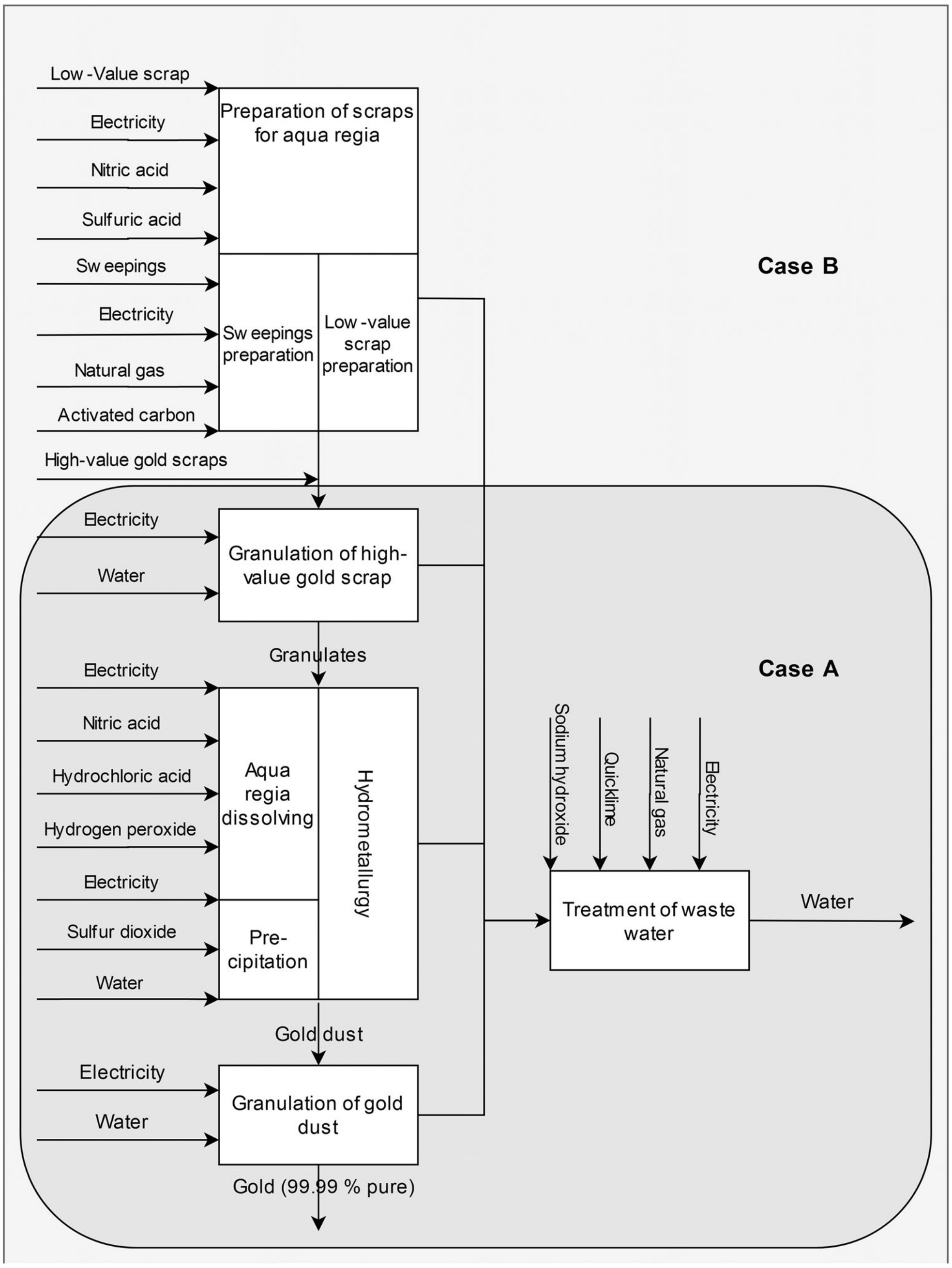


Fig. 3 Schematic diagram of the process of gold refining

In this step, activated carbon is added to the flue gas stream to reduce the emissions (e.g., carbon mono- and dioxide, hydrogen chloride, nitrogen oxides, sulfur dioxide, or mercury). The input of high-value scraps mainly consisting of jewelry and coins is not subject to any further preparation in addition to sampling. Second, a mixture ratio of the three inputs that is suitable for solvation in aqua regia is defined. This mixture is then smelted and sent through small holes of approximately half a centimeter in diameter into water to create small granulates that are easy to dissolve in acid later. The smelting process is electrically heated. The granulated scraps are then dissolved in aqua regia, an acid consisting of a mixture of one part concentrated nitric acid and three parts concentrated hydrochloric acid. The following reaction (Eq. 1) summarizes the process.

$$Au + HNO_3 + 4HCl \rightarrow HAuCl_4 + NO + 2H_2O \quad (1)$$

In this step, electricity is mainly used for keeping the temperature at approximately 90 °C and for peripheral components such as pumps and stirrers. This step forms silver chloride that can be gravitationally separated from the solution. Now the gold has to be precipitated from the solution. One common method is the addition of sulfur dioxide (Adams 2016). Gold is precipitated with sulfur dioxide by the following reaction (Eq. 2):

$$2HAuCl_4 + 3SO_2 + 6H_2O \rightarrow 2Au + 8HCl + 3H_2SO_4 \quad (2)$$

Next, the denser gold fraction, occurring as fine gold dust, can be gravitationally separated from the solution. The fine gold dust is smelted and regranulated for sale. The remaining solution still contains small quantities of platinum and palladium, which are separated in an additional process step. Since this step is not necessary for the refining of the functional unit of 1 kg of gold, no further data on this process step are presented. The remaining chemical solution, together with the other wastewater flows (e.g., the electrolytes from the preparation of low-value scraps), is treated with sodium hydroxide and quicklime for neutralizing the pH value in a central wastewater unit. During this process, hydroxide flakes containing various metals are formed. These flakes are filtered out to form the so-called hydroxide sludge. The wet sludge is then dried with natural gas to reduce its weight and volume for disposal.

The processes related to the aqua regia processes as used in this article (Fig. 3) are then modeled in the LCA software Umberto NXT (ifu Hamburg GmbH). This software was chosen because of its effectiveness in modeling multi-output processes, handling different allocation rules, as well as cost calculations and its good options for visualizing the results, e.g., Sankey diagrams, which are useful when working together with industry partners. The gate-to-gate model was extended to a cradle-to-gate model by using the background processes from the ecoinvent v.3.5 database. Wherever possible, attempts were made to use market datasets for Germany [DE] or countries with a similar technological development level, since the primary gate-to-gate data originate from German factories. Sodium hydroxide is the only exception, and as there are no other data, a global (GLO) process had to be chosen. The processes used are summarized in Supplementary Section c in Table iii. Additionally, for one process, the incineration of sweepings elementary exchanges with their associated environmental impacts from the ecoinvent v.3.5 materials in the category *non-urban air or from high stacks* was used (see Table 1), since we had primary data from emission measurements that fitted well to the materials available in ecoinvent on hand.

To determine the relevant impact categories for the environmental impact assessment related to this inventory, a literature review of 12 different LCA studies was conducted in which gold was assessed either as the main focus of study or as a by-product (e.g., WEEE recycling). The impact categories used in these studies were then aligned with the 14 characterization factors recommended by Hauschild et al. (2013) to generate a consolidated list of characterization factors. In other words, combining the relevant environmental impacts gained from the literature research with the characterization factors recommended by Hauschild et al. (2013) (and thus by the EU initiative ILCD), a comprehensive list of relevant impact assessment methods for the material gold is obtained. A detailed list of all the assessed LCA studies can be found in Supplementary material c. Since five of the articles reviewed used the cumulative energy demand (CED), this parameter will be included in this study, although it was not included in the Hauschild et al. (2013) study.

3 Results

3.1 Gate-to-gate inventory

The data we have collected is based on real, on-site measurements and quantities. In a few cases, consumption quantities could not be allocated exactly to processes. In these cases, reasonable estimates and allocations were made in coordination with the personnel and then validated using literature values or stoichiometric calculations.

For the preparation of low-value gold scraps, data from only one refinery are available. The low-value scraps undergo a different electrolysis process depending on the precious metal contents. In practice, the gold content of the scrap inputs is highly concentrated with each electrolytic separation step of the base metals. Within this preparation, we therefore have several processes that indeed separate or produce other valuable metals at a considerably high purity level, e.g., copper or silver. As we encounter multi-output processes here, we need to apply allocations (see Section 2). Because only one refinery is processing these scraps and because the refinery data are confidential, we agreed to publish only the data allocated for the product output of the prepared low-value scraps (lv). All the processes were modeled in Umberto with the amounts and monetary values of the different in- and outputs. Subsequently, these processes were combined into one process by using allocations according to the ecoinvent system models v.3 (by monetary value) and v.2 (by mass) to bear exactly the same environmental impacts as the disaggregated processes. The aggregated inventory for the electrolytic preparation of the different low-value scraps is provided in Table 1. The material designation "wastewater, internal" means that this wastewater enters the internal wastewater treatment unit and is not directly piped into the municipal sewage system. This process is part of case B, and the mean gold concentration in the prepared low-value scraps is 18%.

For the incineration of sweepings, it was possible to gather the emissions measurements for this process from one company. For the sake of simplicity, substances occurring in trace amounts in the emissions data were disregarded if these substances did not have extraordinarily high-impact factors in one of the impact categories considered in this study. These data were then extrapolated correspondingly on the basis of the mass of the scrap inputs for the average value of all refineries, which can be found in Table 1. This process is part of the aforementioned case B, and the average concentrations of valuable metals in the ash of the incinerated sweepings (si) are as follows: Au, 0.69%; Ag, 12%; Pd, 0.010%, and Pd, 0.08%.

Table 1 shows the data of the granulation of all scrap inputs, namely, the high-value scraps (e.g., jewelry and coins), the low-value scraps subjected to various electrolysis processes, and the incinerated sweepings. This inventory is particularly interesting as it shows the mean ratio of the companies' scrap input flows to the following hydrometallurgical refining step with aqua regia. This ratio is also the ratio used to distinguish between cases A and B introduced in Section 2. The average concentrations of the high-value scrap inputs are as follows: Au, 61%; Ag, 14%; Pd, 4.0%; and Pt, 2.9%.

The inventory data for the hydrometallurgical refining process with aqua regia and the subsequent granulation of gold dust can be found in Table 1.

The companies that provided the primary data had one central wastewater cleaning unit to fulfill the legal regulations for wastewater disposal in Germany. Because these data were not process-specific and since it was concluded from the internal discussions that water is not internally circulated, it was assumed that the amount of wastewater is equal to the input mass of auxiliary materials (e.g., chemicals) plus the non-valuable scrap fraction (see Table 1). The primary process data for this process were scaled down to the *per-amount-of-wastewater-basis* (ww) and then extrapolated using the aforementioned wastewater amount. The carbon dioxide emissions associated with the combustion of natural gas to dry the hydroxide sludge were stoichiometrically calculated, resulting in 1.90-kg carbon dioxide per m^3 of gas (at 288.15 K and 101.325 kPa).

3.2 Cradle-to-gate inventory

Next, the materials of the process inventories, or, so to speak, the foreground system of the LCA model (see Section 3.1), have been extended by the aggregated background processes (see Table iii of the Supplementary material) of ecoinvent to create a cradle-to-gate inventory for the production of 1-kg gold for case B. This condensed table contains in its rows the required energy by energy source and some resulting emissions for the respective aggregated background processes in the columns. The materials required for multiple processes, such as electricity, are not duplicated incorrectly. For example, the production of 3.4-kg hydrochloric acid requires electricity, the generation of which in turn requires coal. This coal is then only represented in the hydrochloric acid production column and not incorrectly entered again in the electricity production column, which only contains the amount of coal needed to produce 140 MJ of electricity. For the scrap preparation, the values were determined on the basis of the allocation by monetary value (see Table 1), as provided in Table 2.

3.3 Life cycle impacts

Extending the cradle-to-gate model to include the characterization factors provides the impact assessment which can be used to analyze some of the environmental impacts of the gold refining process in Germany.

The graph in Fig. 4 shows the environmental impacts for 1-kg Au from the process route of case B for all the relevant impact categories mentioned in Section 2. The figure only shows the results allocated by the monetary value in order not to complicate the graph unnecessarily and since the environmental impacts in this method are higher, we are on the safe side with the conservative results. This approach is a common practice in the LCA field of precious metals. Further information on the abbreviations of the impact categories and their associated units can be found in the Supplementary material Section c. What stands out in the chart is that in all of the impact categories, the hydrometallurgy has the biggest impact and only in five categories its contribution to the overall impact is less than 50%.

Allocation by the monetary value gives far higher results than allocation by the mass because gold often occurs in very small quantities but is very valuable compared with metals such as copper or silver, which occur in rather large quantities. A more detailed analysis shows that a large part of the different results comes from the preparation of low-value scraps. This phenomenon is not surprising since the underlying metallurgical processes produce large quantities of low-value metals such as copper and silver (see Fig. i under Section b of the supplement).

Figure 5 compares the total impact results of the three impact categories land use, HumToxCan, and GWP of the gate-to-gate inventories of case B (see Section 3.1), divided into the five different material types chemicals, electricity, natural gas production, and combustion as well as tap water per 1 kg Au. It is apparent from this figure that the chemicals and electricity are the highest contributing materials. What is striking about the chart is the very high contribution of chemicals to the human toxicity and thus to cancer effects. The contribution of the emissions measurement data from the incineration of sweeping to the impact categories HumToxCan or to land use is insignificant.

A comparison of the impact results of gold scrap recycling obtained in the context of this study as presented in Fig. 4, with the abovementioned ecoinvent v.3.5 LCA datasets on the gold from WEEE recycling and mining, is shown in Fig. 6. For this analysis, the model with allocation by the monetary value was chosen because, on the one hand, this method is the allocation method used in the ecoinvent v.3.5 datasets, and on the other hand, this model results in worse impacts, and with a

Table 2 Cradle-to-gate inventory for the aqua regia process

*	Unit	Electricity, medium voltage (140 MJ)	Hydrochloric acid (3.4 kg)	Hydrogen peroxide (6.4 kg)	Nitric acid (0.88 kg)	Sulfur dioxide (0.93 kg)	Tap water (69 kg)	Sulfuric acid (0.76 kg)	Natural gas (5.7 m^3)	Activated carbon (0.03 kg)	Sodium hydroxide (0.42 k g)	Quicklime (3.4 kg)
Energy carriers												
Coal	g	18	0.90	1.8	0.05	0.125	0.01	0.02	0.04	0.13	0.24	0.02
Crude oil	g	220	170	690	90	137	0.72	42	6.7	3.8	23	320
Gas	l	860	270	1500	160	260	0.77	80	5600	14	44	15
Uranium	mg	180	22	38	0.74	3.4	0.32	0.27	0.31	0.46	2.2	2.1
Hydropower	MJ	8.7	2.5	4.2	0.12	0.38	0.07	0.05	0.03	0.05	0.50	1.23
Biomass	MJ	11	1.6	2.7	0.12	0.22	0.01	0.10	0.02	0.03	0.14	0.04
Geothermal	kJ	70	71	120	2.4	10	0.15	1.00	0.50	1.44	16	0.80
Solar	kJ	2.7	0.63	4.27	0.12	0.07	0.01	0.02	0.02	0.05	0.07	0.40
Wind	MJ	17	0.90	1.5	0.03	0.14	0.004	0.01	0.03	0.02	0.10	0.02
Emissions												
Carbon monoxide	g	19	2.7	6.5	0.42	0.51	0.11	0.16	2.4	0.25	0.50	16
Carbon dioxide	kg	26	2.1	7.3	0.56	0.31	0.01	0.06	0.80	0.21	0.53	3.8
Methane	g	40	5.0	28	0.87	1.8	0.03	0.51	1.8	0.62	1.4	0.46
Nitrogen oxides	g	26	5.0	11	5.0	0.82	0.03	0.55	1.1	0.60	1.4	1.9
Sulfur dioxide	g	26	11	18	3.3	45	0.03	4.9	17	1.0	1.6	1.9
Mercury	mg	9.2	0.72	1.3	0.04	0.07	0.01	0.01	0.03	0.04	0.11	0.02

conservative evaluation we do not run the risk of optimistically representing the study results. It is important to note that the values in this figure have been *reduced by a factor of 10 for WEEE* recycling and by a *factor of 100 for mining* to improve the graphical presentation. The results, as shown in the chart below, indicate that the findings of this study for gold from recycling of high-value scrap have a significant lower cumulative energy demand and global warming potential.

4 Conclusion

The starting point of this study was that there were no LCA data on the recycling of gold scraps in any database and a possibility of closing this data gap in cooperation with refineries willing to help by providing primary data. Refineries usually tend to be rather reserved on such information. The real impact of these data on the overall picture became clearer

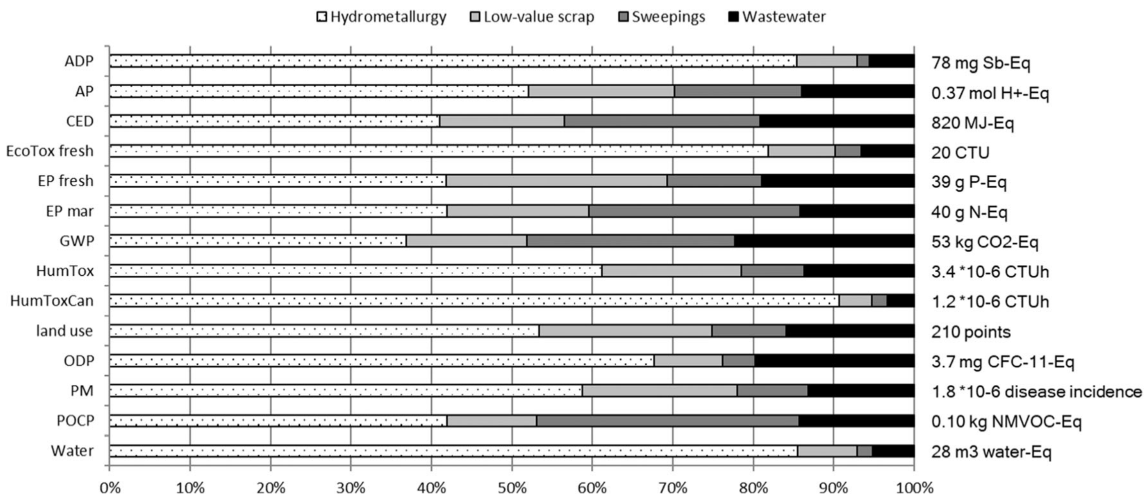


Fig. 4 Environmental impacts of gold refining in Germany allocated by the monetary value

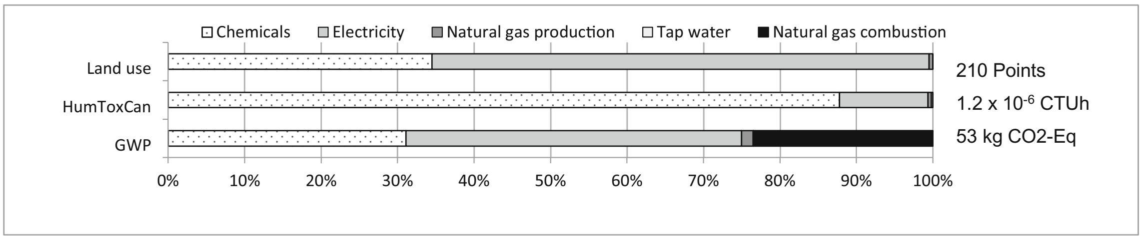


Fig. 5 Impacts of the different material types on exemplary impact categories allocated by the monetary value

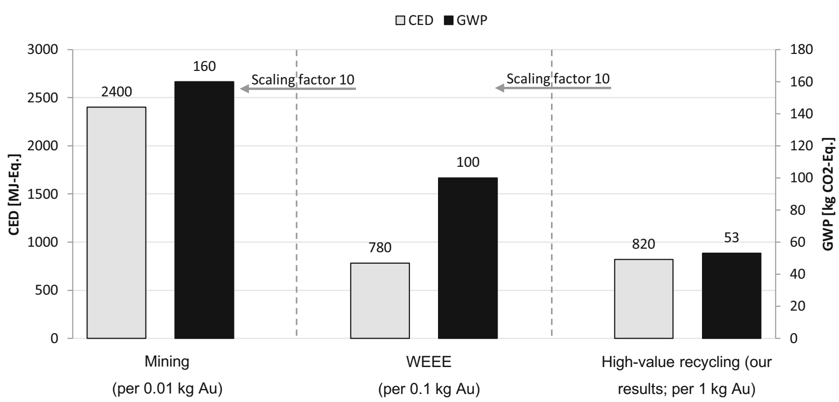
during the study. A notable finding from the literature review was the 23% share of the gold coming from high-value gold scrap recycling. For the existing LCA datasets, this phenomenon immediately meant a 23% lower gold production from deep shafts and large holes associated with well-known environmental damage. Even more astonishing seems to be the fact that in Germany, almost all the processed gold is from gold scrap recycling. None of the refineries interviewed during this study accept dore gold. The only gold produced in Germany that comes directly from mining is found in by-products, e.g., copper concentrates. Although there might be a low probability of misdeclared gold scraps that are actually smelted dore gold smuggled into Germany and laundered in pawnshops, there is strong evidence that the amount is almost zero (Gronwald et al. 2019). The results of this study only apply to gold scrap that is not a primary material or new scrap and therefore only to refineries that only recycle input material from reputable sources. In addition, the refineries analyzed in the work are state-of-the-art precious metal recycling facilities with modern machinery and process flows as well as good waste management systems. These assumptions could be quite different in other countries. To solve the problem of nontransparent supply chains, technology such as blockchain could be used to increase the transparency of the gold origin.

In researching the state of knowledge of LCA concerning gold, the findings that underline the relevance of this work were the major environmental impacts that very small gold amounts today have on products such as smartphones or laptops. The results or the extension of the differences between the environmental impacts of gold scrap recycling with aqua regia and the literature results of previous studies are very positive (see Fig. 6 and Fig. ii in Supplement Section c).

Furthermore, it is interesting to note that more attention is paid to WEEE recycling than to high-value scrap recycling although quantitatively it is the minor fraction of gold recycling and also has worse environmental impacts. As this study is limited to Germany and electricity has a large influence on the overall results for 1 kg of gold from precious metal recycling, the spatial differences in the electricity markets of different countries and thus the spatial differences in the recycling of gold scraps play a significant role. For the end consumer seeking to purchase environmentally friendly gold, the results of the present study mean that the purchase of gold from precious metal recycling facilities in Germany is a good choice as its environmental impact is significantly lower than on world markets.

Nevertheless, there is still a need for further research in the field of LCA and the underlying LCA databases concerning gold. More primary data on the recycling routes in more countries are needed. The data collected in the framework of this study are exclusively from refineries in Germany that reflect well the best available technology. The ecoinvent data on gold from WEEE recycling are based on one recycling plant in Sweden. However, there are also data-related shortcomings in the field of industrial mining. For example, the datasets in ecoinvent v.3.5 include various estimates and extrapolations among the different mining sites. For tailings in particular, new studies have to be conducted to obtain more reliable primary data. Even though few details on the GaBi database are available, both the ecoinvent and GaBi datasets on primary

Fig. 6 Comparison of the different gold routes from ecoinvent with this study's new data on the recycling of gold scraps. Note that the values have been reduced by a factor of 10 for WEEE recycling and by 100 for mining



gold do have one thing in common, namely, that the data almost exclusively rely on corporate reports. Therefore, according to Classen et al. (2009), "it must be assumed that the environmental impacts of gold mining are rather underestimated." Another shortcoming that all databases have in common is caused by the missing data on the primary gold from ASM. To date, three studies have been identified with LCA data on the gold from ASM in Peru and the Philippines (Cenia et al. 2018; Kahhat et al. 2019; Valdivia and Ugaya 2011). To close this gap and include these data in common datasets, it is important to collect more data in different regions and, possibly even more difficult, to determine the market share of the gold from small-scale mining as accurately as possible.

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5.5. *Paper V: An Ecological Analysis of the State-of-the-Art Refinery of High-Value Gold Scraps.*

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An Ecological Analysis of the State-of-the-Art Refinery of High-Value Gold Scraps

Benjamin Fritz, Mario Schmidt

In addition to the numerous applications of gold in the investment, jewelry and industrial sectors, gold also has a bad image because of ecological and social concerns associated with the mining. On the other hand, gold is and has always been recycled. The gold we use today comes from mining (74 %), refining of high-grade gold (23 %) and recycling of electronic scrap (3 %). The 23 % of refining is completely absent in the current life cycle assessment (LCA) databases. LCA databases contain information on outputs from and emissions to the environment and thus make it possible to estimate the environmental impact of different products or services. In this study we were able to collect process data from several German refineries on the most commonly used refining process for high-grade gold scrap, aqua regia. Subsequently, these process data were used to create an ecological analysis with the software Umberto®. The results show that refining of high-grade gold scrap has a much lower environmental impact than mining or recycling of electronic scrap. Thus, high-value gold scrap recycling in Germany results in a cumulative energy demand (CED) of 820 MJ and a global warming potential (GWP) of 53 kg-CO_2-Eq. per kg gold. In comparison, common datasets indicate CED and GWP levels of nearly 8 GJ and 1 t-CO_2-Eq. per kg gold, respectively, for electronic scrap recycling and levels of 240 GJ and 16 t-CO_2-Eq. per kg gold, respectively, for mining. A sensitivity analysis of the model shows that electricity, carbon dioxide in the flue gas and hydrogen peroxide have the largest impact on the GWP. For the end consumer seeking to purchase environmentally friendly gold, the results of this study mean that buying gold from precious metal recycling facilities with high technological standards and a reliable origin of the recycled material is a good choice.

Keywords:

Gold recycling – Gold refining – Life cycle assessment – Environmental impact – Aqua regia

Ökologische Untersuchung der modernen Goldscheidung von hochkarätigem Schrott

Neben den zahlreichen Verwendungsmöglichkeiten von Gold im Investment-, Schmuck- und Industriesektor hat das Edelmetall auch ein schlechtes Image wegen der ökologischen und sozialen Bedenken, die mit dem Abbau verbunden sind. Andererseits wird und wurde Gold schon immer recycelt. Das Gold, das wir heute verwenden, stammt aus dem Bergbau (74 %), der Raffination von Altgold (23 %) und dem Recycling von Elektronikschrott (3 %). Die 23 % der Raffination sind in den aktuellen Ökobilanzdatenbanken überhaupt nicht enthalten. In diesen Datenbanken finden sich Sachbilanzdaten u.a. zur Energie- und Materialerzeugung sowie die Emissionen in die Umwelt und ermöglichen so eine Abschätzung der Umweltauswirkungen verschiedener Produkte oder Dienstleistungen. In der vorliegenden Studie konnten wir Prozessdaten von mehreren deutschen Raffinerien über das am häufigsten verwendete Raffinationsverfahren für Altgold, dem Königswasserprozess, sammeln. Anschließend wurden diese Prozessdaten genutzt, um eine ökologische Analyse mit der Software Umberto® zu erstellen. Die Ergebnisse zeigen, dass das Goldscheiden von hochkarätigem Schrott deutlich geringere Umweltauswirkungen hat als der Abbau oder das Recycling von Elektronikschrott. So ergibt sich für das Recycling von hochwertigem Goldschrott in Deutschland ein kumulierter Energiebedarf (KEA) von 820 MJ und ein Treibhauspotenzial (GWP) von 53 kg-CO_2-Eq. pro kg Gold. Im Vergleich dazu weisen gängige Datensätze für das Recycling von Elektronikschrott einen KEA und ein GWP von fast 8 GJ bzw. 1 t-CO_2-Eq. pro kg Gold und für den Bergbau von 240 GJ bzw. 16 t-CO_2-Eq. pro kg Gold aus. Eine Sensitivitätsanalyse des Modells zeigt, dass Strom, Kohlendioxid im Rauchgas und Wasserstoffperoxid die größten Auswirkungen auf das Treibhauspotenzial haben. Für den Endverbraucher, der umweltfreundliches Gold kaufen möchte, bedeuten die Ergebnisse dieser Studie, dass der Kauf von Gold aus Edelmetallrecyclinganlagen mit hohen technologischen Standards und einer zuverlässigen Herkunft des recycelten Materials eine gute Wahl ist.

Schlüsselwörter:

Goldrecycling – Goldscheidung – Ökobilanz – Umweltanalyse – Königswasser

Analyse écologique de la raffinerie ultramoderne de déchets d‘or de grande valeur

Un análisis ecológico de la refinería de chatarra de oro de alto valor

Paper presented on the occasion of European Metallurgical Conference EMC 2021, June 27 to 30, 2021, online

1 Introduction

1.1 Relevance

The Latin poet Tibullus wrote in one of his famous elegies "in gold many evils are likely to lurk" [1]. Today, more than 20 centuries later, this is still correct.

Gold production does not have a very good public image – both from a social and environmental point of view. During production, deep shafts are dug or wide pits are excavated. Toxic chemicals like cyanide are used [2]. In the so-called artisanal and small-scale mining (ASM), the use of mercury and the destruction of rainforests is publicly known in addition to major social problems [3, 4]. From Ghana we receive pictures from Agbogbloshie, where people recycle waste of electrical and electronic equipment (WEEE) in the smoke of burning cable insulation [5]. Last but not least, voices are raised multiple times about financing of warlords, corruption, and black market trade [6].

One way to counter this image using a scientific method and quantitative figures is the life cycle assessment (LCA). Here, the focus will be on the ecological life cycle assessment, since the methods of social LCA (S-LCA) are not as advanced as yet [7]. In Life Cycle Assessment, products and services are examined for their environmental impact along their life cycle from the extraction of raw materials, through production and use, to disposal. Typically, the individual processes and their process data are modelled in suitable LCA software. The software then has an interface to a LCA database that stores the data relevant to the assessment of environmental impacts for a large number of materials, products or services. This method was developed in the 1970s and is standardized according to ISO standard 14040. The results of this method for gold are in the order of magnitude of 20 metric tons of CO_2-eq. per kilogram of gold – for comparison, the global warming potential (GWP) of copper is 0.0045 and of steel 0.0025 metric tons of CO_2-eq. per kilogram [8-11]. The distribution of GWP between extraction and processing of gold is about 50 : 50 [11]. Due to the high environmental impact of even the smallest quantity, gold has a great influence on product LCA's such as electronic devices. For example, tiny amounts of gold (around 30 mg) carry the largest contribution of the CO_2-equivalents of RAM bars in laptops and these in turn account for about 40 % of the total GWP of the laptop [12]. Ercan [13] comes to similar results for smartphones and Bhakar et al. [14] for different types of computer monitors. High GWP's per product weight can be found for many of the so-called rare earth metals, although from a global perspective the base and bulk metals contribute significant more to the total environmental impacts of the planet because of their high production rates [15].

In order to understand how these environmental impacts are derived one has to realize where the data come from. Most of the data in common LCA databases like ecoinvent or GaBi are gathered from reports. In the mining industry it is common to submit not only financial but also technical and sustainability reports. Note that these reports tend to represent rather a best case as those are voluntary published by the companies. Classen et al. [16] describe this problem as: "Data in this report are based mostly on environmental reports of large multinational companies. However, it must be assumed that these sources represent rather the best practices for gold mining". Another problem with this data is, as it is not specific collected for the

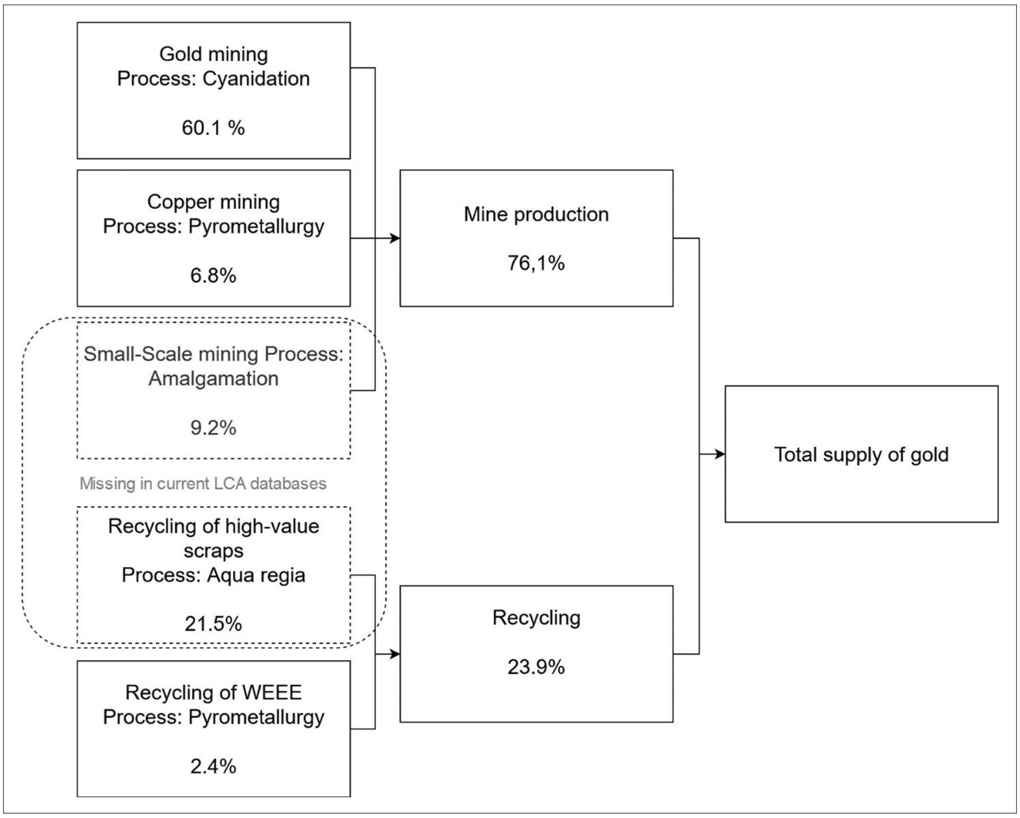

Fig. 1:
Comparison of global shares of different gold production processes; the dashed lined boxes are missing in common LCA databases (Figure adapted from Figure 8.2 in [17])

purpose of a LCA, some of the necessary data are missing or not fitting in the typical scheme of a LCI. If, and this is the normal case, not all relevant data are available for every mine, existing data from one mine are transferred to missing data of another mine. The reference value is usually the quantity of gold or ore mined. This means that some of the values in the life cycle inventories (LCIs), such as chemicals or emissions, are adjusted from a source other than the original mine by scaling them according to production volumes. In other words, ecoinvent assumes an analogy between the different mines. This process was already described in Fritz [17] and is referred to as Intersystemic-Data-Scaling (IDS).

The total production of gold in 2019 was about 4800 metric tons and has been relatively constant over the last 10 years [18]. This amount can now be classified according to various criteria such as countries or applications. In the field of LCA, however, it makes sense to divide production according to its different processing techniques, as these are the main source for the LCA inventories.

Gold originates from two primary routes: recycling and new mining. Newly mined gold accounts for 75 % of the market [18]. It can further be subdivided into gold, which is extracted hydrometallurgically by cyanide leaching, produced as a by-product of copper ore, and amalgamated in ASM. The recycling of gold can be divided mainly into hydrometallurgical processing of scrap gold and pyrometallurgical processing of WEEE [19]. When analyzing the representation of these routes in common LCA databases it becomes obvious that the route of ASM and high-value refining are missing [11, 20]. Figure 1 shows an overview of global shares of different gold production processes.

In our previous studies the problems in the common life cycle databases for the material gold [17] and the environmental impacts of the missing route of high-value gold scrap recycling [21] were treated. Based on the findings of Fritz [21], the aim of this article is to identify the modes of transport and the parameters with the greatest influence on the environmental performance of gold from high-value scrap recycling and to generate recommendations for action to improve this.

1.2 Process description

There are several gold refining processes. The process used depends mainly on the size of the refinery and the type of input material [22]. Certain processes, such as Miller chlorination or Wohlwill electrolysis (their environmental performance can be seen in Figure 7) are better suited to refine primary materials from mines such as doré (impure gold bar created at mines that needs to be further refined) gold on a large scale. Other processes, such as aqua regia, are better for refining secondary high-value gold scraps [23-25]. More precisely, the aqua regia process is recommended for refining high-value (>75 % Au), non-doré scraps, since it is the fastest, simplest and most robust process [19]. It appears that the aqua regia process can therefore be regarded as a representative method for recycling high-value gold scraps.

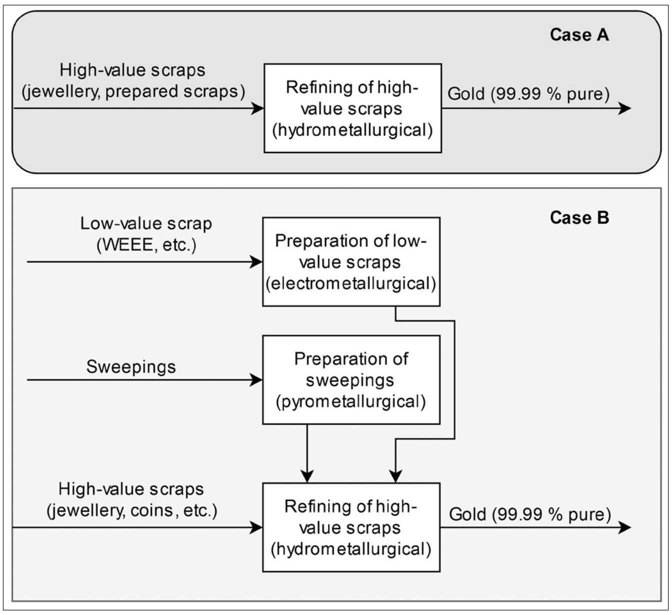

Fig. 2: The two different scenarios examined in this study

Depending on their economic and technological choices, different refineries will recycle different input scrap qualities. In practice, this condition means that there are various processes, mainly electro- and pyrometallurgical processes, to transform the input scraps of different qualities into scraps with concentrations suitable for the aqua regia process. In order to make this as meaningfully as possible in this study, we will differentiate between two cases (Figure 2). Case A will be the ceteris paribus hydrometallurgical aqua regia refining of high-value gold scrap inputs. Case B is an extension of case A with the above-mentioned scrap preparation processes in a ratio based on the mean values of primary company data as we witnessed during the on-site visits in this study (for more details see section 2). The ratios derived from the quantities of low- and high-value scraps as well as sweepings can be seen in the input arrows of the process "granulation of scrap" in Figure 4. Note that the preparation of low-value scraps condenses several different processes for the different scrap input qualities for reasons of simplicity. Figure 2 shows cases A and B.

A general process flowsheet for the aqua regia process as used in this paper is shown in Figure 4. The first step is to prepare the input for hydrometallurgical refining with aqua regia to guarantee a mixture ratio that is suitable for the aqua regia treatment. The preparation of low-value scraps is highly dependent on the different types of electrolysis processes, depending on the different qualities of the input material and the technologies available in the refinery. Low-value scraps are for example precious metal coated, stamping scrap or electronic scrap. The preparation of sweepings entails the incineration of the inputs, which burns off all the organic material. In this step, activated carbon is added to the flue gas stream to reduce the emissions. The input of high-value scraps mainly consisting of jewelry and coins is not subject to any further preparation in addition to sampling. Second, a mixture ratio of the three inputs that is suitable for solvation in aqua regia is defined. This mixture is then melted and sent through small holes of approximately half a centimeter in diameter into water to create small granulates that are easy to dissolve in acid later. The melting process is electrically heated. The granulated scraps are then dissolved in aqua regia, an acid consisting of a mixture of one part concentrated nitric acid and three parts concentrated hydrochloric acid. Reaction (1) summarizes the process.

$$Au + HNO_3 + 4HCL \rightarrow HAuCl_4 + NO + 2H_2O \quad (1)$$

In this step, electricity is mainly used for temperature control at approximately 90 °C and for peripheral components such as pumps and stirrers. Silver chloride is formed that can be gravitationally separated from the solution. Subsequently, the gold has to be precipitated from the solution. A common method is the addition of sulfur dioxide [19] that precipitates gold by Reaction (2):

$$2HAuCl_4 + 3SO_2 + 6H_2O \rightarrow 2Au + 8HCL + 3H_2SO_4 \quad (2)$$

The denser gold fraction, occurring as fine gold dust, can be gravitationally separated from the solution. This fine gold dust is melted and granulated again for sale. The remaining solution still contains small quantities of platinum and palladium, which are separated in an additional process step. Since this step is not necessary for the refining of the functional unit of 1 kg of gold, no further data on this process step will be presented. The remaining chemical solution, together with the other wastewater flows (e.g. the electrolytes from the preparation of low-value scraps), are treated with sodium hydroxide and quicklime for neutralization in a central wastewater unit. During this process, hydroxide flakes are formed that contain various metals. These flakes are filtered out to form the so-called hydroxide sludge. The wet sludge is then dried with natural gas to reduce its weight and volume before disposal.

2 Method

In order to finally close the LCA data gap of the missing 21.5 % share of the total gold supply from recycling (see Figure 1), an extensive study was conducted firstly on the processes commonly used to recycle gold scraps and secondly how these processes work. Subsequently, primary data were gathered for prior detected processes from a number of state-of-the-art precious metal recycling facilities in Pforzheim with a production volume of approximately 50 tons of gold per year. For reasons of confidentiality, the facilities must remain anonymous, but these facilities can be considered to be a best practice case for the gold scrap recycling in Germany and thus in highly industrialized countries [21].

To use the collected data for environmental assessments such as LCA, certain general specifications according to ISO standard 14040 for LCA were agreed upon. The system under investigation, or in other words the foreground system, ranges from the preparation of the refinery input materials to the product output of 1 kg of 99.99 % fine gold granulate. The 1 kg of 99.99 % also represents the functional unit (FU). The system boundary is a cradle-to-gate system. This cut-off system model is typically used in recycling. For the transportation of the scraps to the refinery primary data on shipping quantities and weights broken down by the different qualities of scrap was on hand.

An analysis of the shipping data showed, that most of the deliveries are for high-value scraps. These deliveries have compared to low-value scraps and sweepings the lightest weight. The shipping distance has a median between 600 and 700 km. From interviews with the refineries as well as with goldsmiths and shops, we know that the modes of transports are parcel service companies, cash-in-transit as well as trucks. The goldsmiths and shops often have special insurance on loss of transports so they use regular parcel services quite often. Since it is almost impossible to get data about business practices or routing of cash-in-transit services, we assume only practices of regular shipping companies. For regular parcel services, we assume a logistic

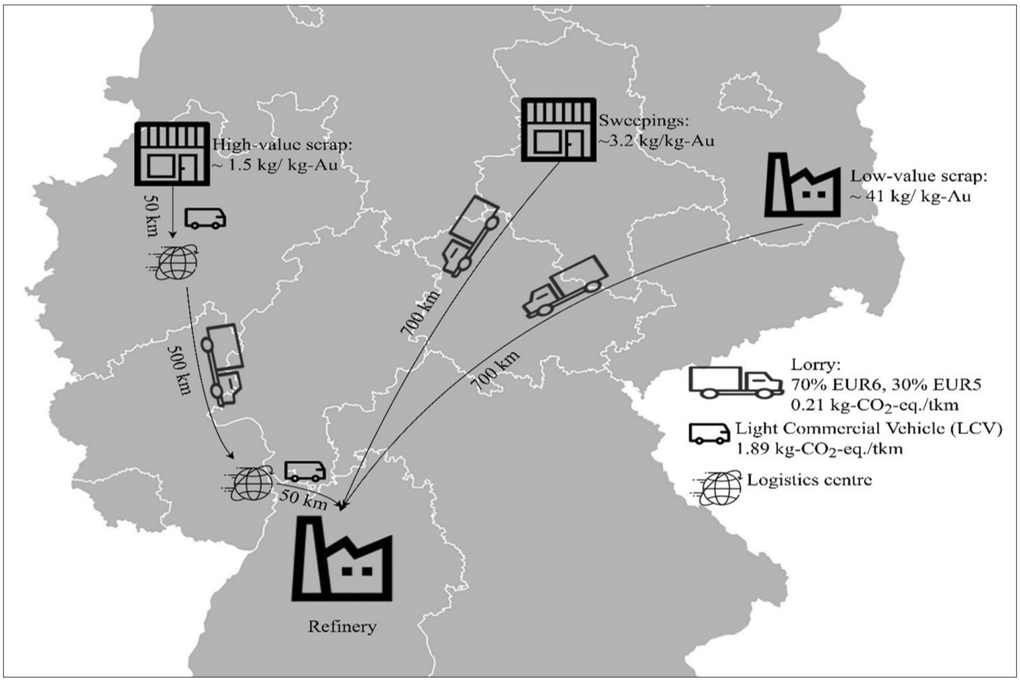

Fig. 3:
Modes of transport for the three scrap inputs in this study

center approximately 50 km from the origin/destination where parcels get loaded from/to light commercial vehicles (LCV) to/from trucks. For low-value scraps and sweepings we only assume trucks due to higher masses. In all modes of transport, for trucks a share of 70 % EUR6 and 30 % EUR5 is assumed, hence this is the current mix of lorries in Germany [26]. A special feature of the delivery of high-value gold scrap is, that due to the high value and low volume, private deliveries also occur. At first glance, these would have quite high impacts, as the economies of scale are naturally much smaller than with professional transport companies. However, one quickly moves into areas that are difficult to quantify, for example if the delivery is combined with a business lunch or a private activity in the region. For more details on transport activities in this study see Figure 3.

A common problem in LCA is that metals often occur as byproducts in multi-output processes, e.g., as ore bodies in mining or as scraps in recycling containing multiple valuable fractions [21]. As a result, the environmental impacts of these processes must be distributed among the value-adding precious metals. The most common method for solving this problem is allocation by mass or monetary value. Allocation by mass means that the metal with the largest quantity is assigned the highest environmental impacts, and vice versa, the metal with the smallest quantity is attributed the lowest impacts. Allocation by monetary value means that the metal with the highest added value in the process (mass times the market value) will have the highest impacts [27]. An average price over several years (e.g. five years) is taken as the price. Since gold is often associated with other base metals, the allocation according to mass proportions cannot adequately reflect the main purpose of the mine [28]. The allocation by monetary value, however, captures the driving force of mining, namely profit. The processes related to gathered primary data are then modeled in LCA software Umberto NXT. This software was chosen because of its effectiveness in modeling multi-output processes, handling different allocation rules as well as cost calculations and its good options for visualizing the results, e.g., Sankey diagrams, which are beneficial when working together with industry partners. The gate-to-gate or foreground model was extended to a cradle-to-gate model by using the background processes from the ecoinvent database. The database version was updated to v.3.6 compared to the analysis from Fritz [21]. Wherever possible, attempts were made to use market datasets for Germany [DE] or countries with a similar technological development level since the primary gate-to-gate data originate from German factories. Sodium hydroxide is the only exception, and as there are no other data, a global (GLO) process had to be chosen. The processes used are summarized in Table 1. Additionally, for one process, the incineration of sweepings elementary exchanges with their associated environmental impacts from the ecoinvent v.3.6 materials in the category "non-urban air or from high stacks" were used (see Figure 4), since we had primary data from emission measurements that fitted well to the materials available in ecoinvent at hand.

The impact categories analyzed in this study are the global warming potential (GWP), the cumulative energy demand, land-use and the eco-scarcity. GWP and energy-use were

Table 1:
Ecoinvent v.3.6 processes and their geographical locations used to develop the cradle-to-gate inventory

Process name	Geography name	Purpose in this study
market for transport, freight, lorry 7.5 to 16 metric ton, EURO6	Europe [RER]	Transportation of scraps
market for transport, freight, lorry 7.5 to 16 metric ton, EURO5	Europe [RER]	Transportation of scraps
market for transport, freight, light commercial vehicle	Europe, without Switzerland	Transportation of scraps
market for electricity, medium voltage	Germany [DE]	Temperature regulation, stirring and wastewater treatment
activated carbon production, granular from hard coal	Europe [RER]	Cleaning of flue gasses
market for tap water	Switzerland [CH]	Cooling and solidifying gold granulates
nitric acid production, product in 50 % solution state	Europe [RER]	Dissolving gold in aqua regia
market for hydrochloric acid, without water, in 30 % solution state	Europe [RER]	Dissolving gold in aqua regia
hydrogen peroxide production, product in 50 % solution state	Europe [RER]	Dissolving gold in aqua regia
market for sulfuric acid	Europe [RER]	Electrolysis in low-value scrap preparation
market for quicklime, milled, loose	Switzerland [CH]	Adjusting the pH value
natural gas production	Germany [DE]	Smelting, incineration and drying
market for sodium hydroxide, without water, in 50 % solution state	Global [GLO]	Cleaning of wastewater
treatment of wastewater from wafer fabrication, capacity 1.1 E10 l/year	Switzerland [CH]	Cleaning of wastewater

chosen, since they are very far developed and relevant in many discussions e.g. carbon pricing or SDGs. Land-use was chosen, since this is prominent in discussions about metal production and it is able to give interesting insights when modelling different power scenarios. Eco-scarcity is a so-called single-score method developed in Swiss in the 80s [29]. Single-score methods and in particular the ecological-scarcity have been the subject of discussions for several years now. Note that these methods have the advantage of aggregating all the environmental concerns' in one number, but at the stake of qualitative choices and values.

After testing and validating the model, it was calculated about 50 more times, while each time one value in the foreground system was increased by 20 %. This sensitivity analysis was particularly useful in identifying the parameters where changes have the highest impact on the overall results. This was used to identify and subsequent quantify recommendations to improve the environmental perfomance. Finally, the influence of the energy grid mix was analyzed and a comparison of the aqua regia process in this study but with a South African grid mix with the Rand-Refinery was made.

3 Results

3.1 Product system

The data collected are based on real, on-site measurements and quantities. In a few cases, consumption quantities could

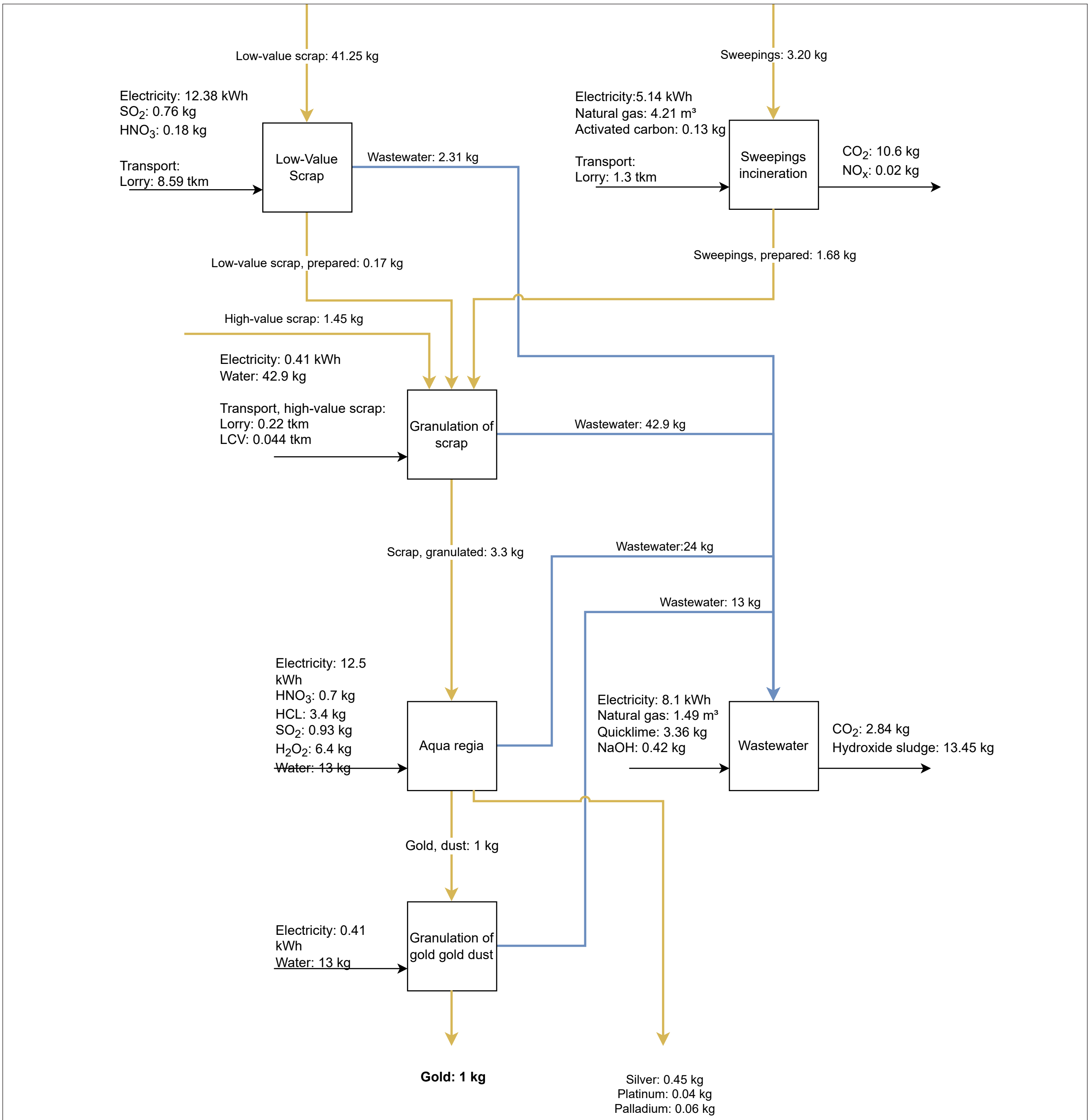

Fig. 4: Overview of the gold refining product system considered in this study

not be allocated exactly to processes. In these cases, reasonable estimates and allocations were made in agreement with the personnel and then validated using literature values or stoichiometric calculations. Figure 4 illustrates the process data used in this study.

3.2 Life cycle impacts

Figure 5 shows an overview of the environmental impacts for the impact categories broken down in process steps. The processes from scrap granulation until gold dust granulation (see Figure 4) were condensed into the process hydrometallurgy. All the transports were separated from their processes in order to see their contributions on the whole model. What stands out in the figure is that the hydrometallurgical phase has the highest contribution in all impact categories. A closer look at the figure shows that land-use is the only impact category analyzed with transport contributing more than 5 % to the total impact.

Figure 6 illustrates the breakdown of the environmental impacts in their material classes. It is apparent from this figure that electricity followed by chemicals are the most contributing material classes to the overall results. Note that values smaller than 0.1 % are not displayed. Interestingly, the data show that natural gas has almost no relevance on land-use. Furthermore, the breakdown of GWP and eco-scarcity appears to be quite similar. These two are

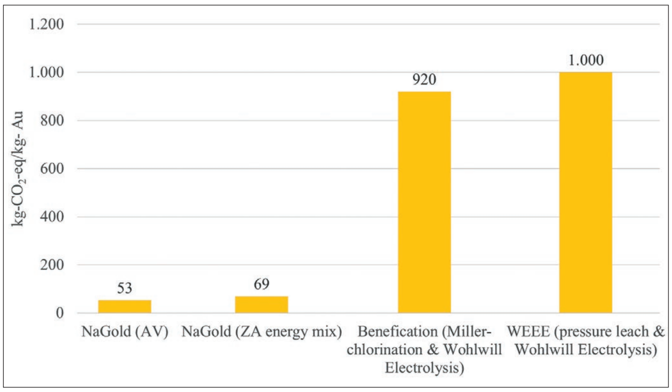

Fig. 7: Impact of different material types allocated by monetary values

also the only impact categories where transportation has a contribution larger than 0.1 %.

The results of the comparison with two other gold routes are summarized in Figure 7. The first alternative route is refining of gold from WEEE using pressure leaching and a top blown rotary converter to treat the anode slime followed by Wohlwill electrolysis to refine the gold. The second process is from a major refinery, the Rand-Refinery in South Africa that uses Miller chlorination and Wohlwill electrolysis to refine primary materials from mines such as doré gold on a large scale [30]. In addition, the results of this study were modelled again with a South African

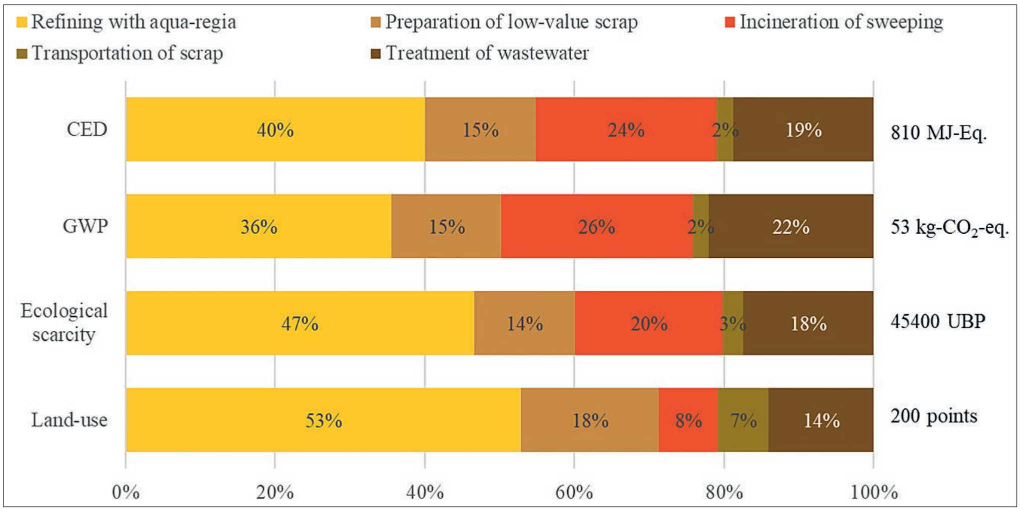

Fig. 5: Environmental impacts of high-value gold refining in Germany by processes

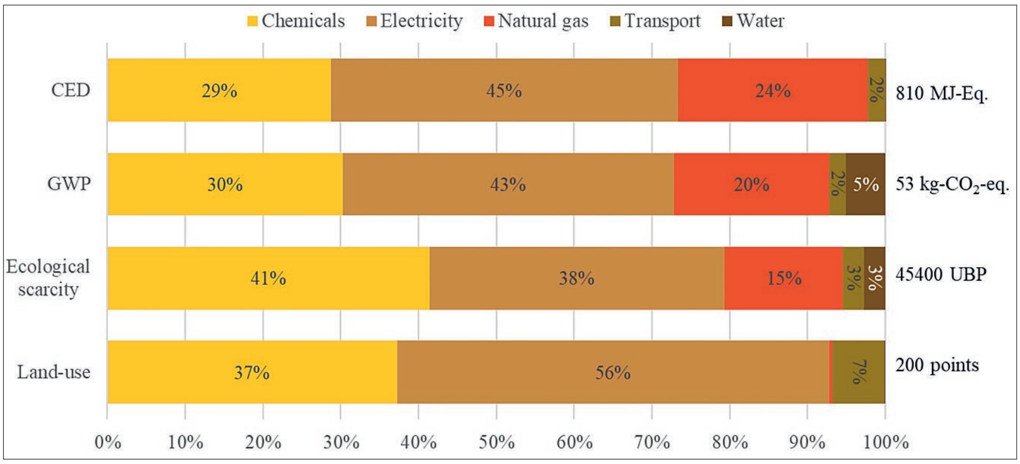

Fig. 6: Environmental impacts of gold refining in Germany by material types

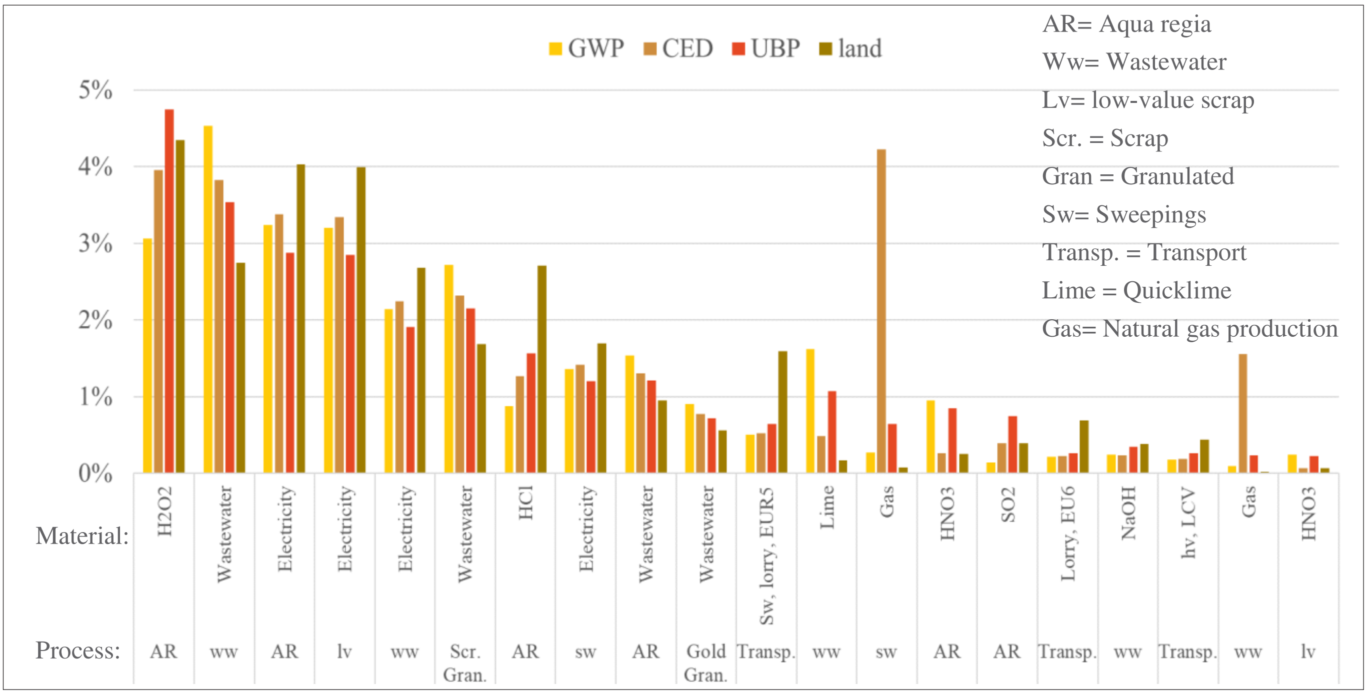

Fig. 8: The top 20 most sensitive processes (measured in percentage change to the overall result)

power mix. The difference between the hydrometallurgical refining using the aqua regia as witnessed in this study and other gold refining routes was significant even when using the South African power mix. It is important to note the different qualities of the input materials for the routes.

Figure 8 presents the experimental data of the sensitivity analysis in all impact categories analyzed in this study. In more detail, it shows the impact on the overall results that a change of 20 % of the in-/output quantity of a material has in percentage (see last paragraph of section 1). The Figure displays a selection of the top 20 of all the materials. It can be seen that the most sensitive materials are in the field of energy supply (electricity and gas). Note that the high value for CED for natural gas production is typical for production processes of energy carriers because the inherent energy of natural gas being so high compared to the energy demands for extraction. However, the most sensitive material overall is the chemical H_2O_2. The chemicals HCL, quicklime, SO_2, NaOH and HNO_3 can also be found in the top 20.

3.3 Recommendations to improve the environmental profile

The analysis of the contribution of the production phases (see Figure 5) and material classes (see Figure 6) in combination with the findings from the sensitivity analysis (see Figure 8) help identifying recommendations to improve the environmental profile of high-vale gold recycling. The first recommendation for improvement is to use clean energy from regenerative sources like wind or solar power. Second, instead of natural gas for incineration of sweepings and drying of waste slags, hydrogen (produced with regenerative energy) could be applied. Next, the transport phase that contributes depending on the impact category between 2 to 7 % is a good way to decrease the environmental impact without or little affecting internal processes. An option that was mentioned by one goldsmith interviewed was, to set specific dates and regions for picking up scraps to minimize small quantity deliveries. Furthermore, it can be recommended to use other neutralizing agents than calcium. When neutralizing with limestone ($CaCO_3$) the chemical reaction creates a substantial amount of CO_2. Quicklime (CaO) on the other hand buries similar CO_2 emissions in its upstream production chain. Neutralisation of the pH-value with sodium hydroxide (NaOH) can be a good alternative when sourcing it from a water-electrolysis with clean and regenerative energy. The neutralizing agent ammonia (NH_3) could be an opportunity for a zero-waste concept. It has substantial amounts of CO_2 emissions in its upstream production chain but produces ammonia solution (also known as ammonia water) as a by-product, which has various applications like food and wood production or household cleaners. Besides that, the precipitation agent can also be substituted by alternatives. The amounts of the alternative precipitations agents were calculated using stoichiometry and following the reactions in Adams [19]. Of the most common chemicals sulphur dioxide (SO_2), ferrous oxide (FeO_x) and formic acid (HCOOH) used to precipitate gold from aqua regia, sulphuric acid (H_2SO_4) is recommended. In contrast to ferrous oxide and formic acid, it has lowest environmental impacts in the impact categories studied. Sodium metabisulfite is another common alternative, but it is not yet included in LCA databases. However, it can be assumed that due to its chemical similarities to SO_2, the environmental effects are very similar to those of sulphuric acid, except that more waste is produced and therefore it is not to be favoured. Last, one company has already compensated for their remaining greenhouse emissions on the basis of our previous study [21]. This could be one last option after all other alternatives and reduction potentials having been considered and if the compensation is confirmative with certain standards (e.g. no nuclear power).

Further analysis showed, that when applying recommendations for improvement on the LCA-model a global warming potential of 22 kg-CO_2-eq is calculated. This is achieved under the best case conditions of using 100 % onshore wind power, substituting natural gas for hydrogen and quicklime for sodium hydroxide from both CO_2-neutral electrolysis. For a yearly production of 80 tons of gold in Germany, this would lead to a total saving of 2480 t of CO_2-eq.

4 Discussion

The environmental impacts associated with the material gold are very high and so are the uncertainties and assumptions in the common LCA databases. One big problem is that the route of high-value gold scrap recycling, constituting for 20 % of the world's gold production is missing in the common databases. After covering these two topics in previous articles [17, 21], this article goes more in depth about some missing aspects about transport as well as helping to give recommendations for improvement of the environmental profile. The transportation phase is contributing to around 2 % of the global warming potential. Some recommendations for action that could be derived from a sensitivity analysis of the LCA model are the application of renewable energies as well as hydrogen for smelting. For the chemicals used in aqua regia, sulfuric acid (H_2SO_4) is recommended for precipitation. Sodium hydroxide (NaOH) from water electrolysis with renewable energies like e.g. solar power is recommended as neutralization agent. The results of this study are very valuable, as gold demand has always remained very steady notwithstanding financial or even right now health crises and the pressure on the industries to react to climate change is rising.

In this study, we used primary and secondary data to understand the modes of transport for high-value gold scrap recycling. Furthermore, we measured the influence of all the primary process data like energy or chemical demand on the overall environmental impact by applying a sensitivity analysis with the LCA-Software Umberto. Through analyzing the most sensitive materials and the material groups with the highest influence, we identified a best-case scenario leading to a 60 % reduction in global warming potential.

Contrary to expectations, the influence of transportation of gold scraps was lower than expected. This is because most of deliveries are done by parcel transportation service with great efficiencies. Surprisingly, little differences were found in the proportionate analyses between the impact categories eco-scarcity and GWP. One interesting finding is, that comparing the results of the refining process in focus of this study with results for the alternative processes of WEEE refining or the Rand-Refinery-Process the environmental impacts are more than factor 10× lower. This was even the case when applying Rand-Refineries energy mix to this study's LCA-model. A possible explanation for this might be that the input material of high-value gold scrap recycling is very pure and high in gold content compared to WEEE or doré. One unanticipated finding was that, hydrogen peroxide (H_2O_2) is the most sensitive material. This result may be explained by the fact that hydrogen peroxide is used in the phase of hydrometallurgy and is part of the material class chemicals, which are both high contributing to the overall environmental impact. Additionally, H_2O_2 is used in substantial amount and has quite high environmental impact factors (e.g. × 1.56 in GWP) as a lot of energy is required to produce this unstable compound.

These findings cannot be extrapolated to all similar refineries as the data in this story is based on only a handful of companies. A note of caution is due here since the primary company data represents rather state-of-the-art precious metal recycling facilities with modern machinery and process flows as well as good waste management systems. Furthermore, the companies are both based in Germany, which has rather good environmental laws like wastewater or emission regulates. Another source of uncertainty is the best-case scenario as this did not consider all the consequence in depth associated with the better alternatives e.g. transport, handling and storage of hydrogen. The same applies for the sensitivity analysis, as consequences and independences of the materials were not considered when alternating the values.

There are still many unanswered questions about the rather restrained actors in the supply chain of gold. More data is needed from more facilities around the world. There is abundant room for further progress in determining costs for the proposed alternatives. An analysis like material flow cost accounting might be useful for this. Further research should be undertaken to develop more realistic scenarios additionally to the here developed best-case scenario. For instance, a model to predict future energy grids could be attached to the LCA-model in this study. To develop a full picture of the model parameters, additional Monte-Carlo simulations will be needed.

Companies using aqua regia to refine gold but also in a broader sense any hydrometallurgical refinery seeking to become more environmental friendly may consider using renewable energies, hydrogen ovens, high utilized transports as well as other neutralization agents than (quick-) lime. With these steps it is even for a hydrometallurgical process possible to save more than 50 % of greenhouse emissions.

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5.6. Paper VI: Climate Change vs. Circular Economy: Challenges of the Most Common Route for Recycling Gold from WEEE

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Climate Change vs. Circular Economy: Challenges of the Most Common Route for Recycling Gold from WEEE

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Abstract: Gold production poses significant environmental challenges, including resource depletion, CO_2 emissions, and toxic chemical usage. Similarly, improper WEEE management harms the environment. However, WEEE contains valuable metals such as gold, making it central to circular economy (CE) strategies and an alternative to mining. This study assesses the climate impact of pyrometallurgical gold recovery from WEEE using life cycle assessment (LCA). The study found that the carbon footprint of producing gold pyrometallurgically from WEEE is 2000 kg CO_2eq/kg. These emissions are largely tied to the carbon content of waste, meaning that low-carbon energy sources have a limited impact. This creates a conflict between CE goals and CO_2 reduction. Scenario analysis shows that utilizing waste heat for district heating significantly lowers emissions. The other strategies used to improve the environmental performance include separating the plastic fraction before smelting, using biogenic plastic in WEEE, and carbon capture and storage (CCS). Transport accounts for just 10% of the total carbon footprint. Future regulations must address multiple factors—EEE production, waste management, smelter infrastructure, global socioeconomic dynamics, and consumer behavior—as higher recycling rates alone will not solve WEEE challenges.

Keywords: LCA; carbon footprint; WEEE; gold; recycling; pyrometallurgy; CO_2; circular economy; metals

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1. Introduction

Waste electrical and electronic equipment (WEEE) poses significant ecological challenges, as does traditional gold production through mining. However, gold can also be produced through the recycling of WEEE, providing a more environmentally friendly alternative that avoids gold mining and reduces WEEE.

According to the UN waste monitor, around 62 billion kg of WEEE was generated in 2022, of which only 13.8 billion was recycled in compliance with official standards [1].

Urban mining offers a huge potential for WEEE. While the concentration of gold in primary ores is just a few grams per ton, in WEEE, gold concentrations as high as 980 g/t in mobile phones or 420 g/t in printed circuit boards (PCBs) are common [2,3]. However, WEEE is a heterogeneous input material, with varying material compositions, forms and particle sizes. It is a complex input that requires different extractive technologies to ores [4]. However, the actual global volumes of gold obtained through recycling are low, with only about 3% of annual gold production coming from WEEE recycling [5]. Furthermore, technology appliances account for only around 7% of the annual global gold demand [6].

The most common route for producing gold from WEEE on an industrial scale involves pyrometallurgical processing using a copper smelting process [7]. Recycling gold from

WEEE is also a prime example of Reuter's "metal wheel", where copper metallurgy serves as the enabler of the circular economy in gold recovery from WEEE [8]. WEEE is typically co-processed alongside sulfide copper concentrates in existing copper smelters, where it is added as an additional feedstock—resulting in the combustion of the plastics contained in the WEEE. The plastic fraction also serves as an energy carrier and reducing agent in the process. The majority of gold recovered from formal recycling comes from around ten companies, including Mitsubishi Materials Corporation (MMC) and DOWA ECO-SYSTEM in Japan, Aurubis in Germany, Boliden Group in Sweden, Glencore in Canada, and Umicore in Belgium (for more details please find Supplement Table S2).

The informal recycling of WEEE, such as in Accra Market, Agbogbloshie (Ghana), involves burning WEEE to remove plastics and recover metals under hazardous conditions. While the exact fate of the recovered metal fractions is not fully known, the UN Waste Monitor states that some valuable materials are sold to companies in the Global North for further recycling. Additionally, some small-scale informal recyclers use toxic chemicals to directly retrieve the gold from, for example, PCBs. This process is carried out in their houses or backyards without sufficient safeguards for human health or the environment [9,10].

According to Nuss and Eckelman, gold is among the metals with the highest specific CO2eq per mass in the periodic table, with a CO_2eq of around 30,000 CO_2eq/kg Au [11,12]. Surprisingly, the annual impact on climate change from copper mining (≈182 Mt CO_2eq/a) 27 billion kg are mined annually similar to the impact of gold mining (236 Mt CO_2eq/a) when using the market datasets in ecoinvent v.3.11 [6,13]. The recycling of high-value EoL scrap on the other hand is known to have a very low carbon footprint of around 40 kg CO_2eq/kg Au [14].

A common method of quantifying environmental impacts along the life cycle of products and materials is life cycle assessment (LCA). A literature screening of LCA studies in the field of WEEE yielded three prior studies performing a thorough analysis of gold. All three studies are comparative LCAs that analyze the environmental impact of different routes of producing gold from WEEE.

In a study that aimed to identify the most eco-friendly recycling technique, He et al. presented LCA results for the mechanical, pyro-, hydro-, electro- and biometallurgical recycling of gold from PCBs [15]. Unfortunately, the study did not include their LCI tables, making it difficult to analyze their results. The impact of the pyrometallurgical recycling route on climate change is reported to be 5840 kg CO_2eq/kg Au. The impact of all the different routes lies between 1420 kg CO_2eq/kg Au and 35,400 kg CO_2eq/kg Au.

Rezaee et al. performed a comparative LCA on six different hydrometallurgical processes used to recycle gold from PCB powder [16]. Their results show that the climate impact lies between 1.17 kg CO_2eq/kg PCB and 46.6 kg CO_2eq/kg PCB. Unfortunately, this study did not report their results per metal. Based on the composition of the input material, we estimated the CO_2eq for the production of gold. Using economic allocation, the carbon footprint is between 10,000 kg CO_2eq/kg Au and 400,000 kg CO_2eq/kg Au. The lowest result is slightly higher compared to those of He et al., who found that for hydrometallurgical recycling, the carbon footprint is 7860 kg CO_2eq/kg Au [15].

Li et al. compared two different recycling methods, the hydro- and the pyrometallurgical routes, with their own novel technique using LCA [7]. The results showed that their novel approach had the lowest CO_2eq, with around 1230 kg CO_2eq/kg Au compared to 17,900 kg CO_2eq/kg Au for the hydro- and 57,900 CO_2eq/kg Au for the pyrometallurgical route. It is not exactly clear why the values for pyrometallurgical recycling in this study are so high. One major difference between this and the other studies is that the authors do not use the cut-off approach; therefore, the copper scrap added to the smelter enters the system with an additional environmental burden.

In this study, we conducted an LCA analysis of the carbon footprint of recycling gold from WEEE through pyrometallurgical recycling in copper smelters, the most commonly used method. We highlight the challenge of decarbonizing WEEE recycling due to the fossil-based plastics embedded within the scrap input, which are burned during processing. As a result, standard decarbonization measures, such as using renewables in the energy mix, have limited effectiveness. We use scenario analyses to explore alternative solutions.

2. Materials and Methods

2.1. LCA Model

This study focuses on an LCA of the Rönnskär smelter, as conducted by Classen et al. [17] (Part IX, 5.2). This process has also been identified by Bigum et al. [18] as the most comprehensive for the smelter phase of WEEE recycling.

Rönnskär is a copper smelter in Sweden run by the company Boliden. The smelter uses Kaldo furnace technology to add WEEE, together with lead concentrates, to their smelter inputs prior to mixing the resulting intermediate black copper with the primary copper route in the converter process (using a PS converter) [4].

Classen et al. provide a detailed description of an LCI system for WEEE recycling in the Rönnskär refinery [17] (IX, 5.2). This system is used in the ecoinvent process for recycling gold from electronic scrap. Because this system is described in such depth and the pyrometallurgical route for WEEE refining is today's most widely used process, we use Rönnskär's system to gain a deeper understanding of the gold recycling process and its environmental impact. In this analysis, we further refined ecoinvent's assessment by subdividing the process into several different steps (see Tables 1–5).

Table 1. LCI table for the copper conversion of WEEE based on Classen et al. [17] (Part IX, 5.2).

Conversion			
Flow	**Amount**	**Unit**	**Scenarios**
Input			
WEEE	2.72	kg	all
Electricity from Swedish grid	0.126	kWh	all (changed to ROR in SC2)
Smelter infrastructure	8.35×10^{-11}	unit	all
Quicklime	1.02	kg	in SC1, 2 and 3 adjusted to 0.0969 kg
Output			
Metal values from WEEE in blister copper	1	kg	all
Lead	0.0436	kg	all
CO_2 to air	2.70	kg	SC1, 2, 3
Heat (used for district heating as CH_4 substitute)	23.5	MJ	only SC3

Table 2. LCI table for the electrowinning of cathode copper from WEEE based on Classen et al. [17] (Part IX, 5.2).

Electrowinning			
Flow	**Amount**	**Unit**	**Scenarios**
Input			
Metal values from WEEE inblister copper	60.4	kg	all
Anode refinery infrastructure	5.65×10^{-9}	unit	all
Electricity	12.5	kWh	all (changed to ROR in SC2)
Natural gas	1.47	MJ	in SC2 adjusted to 0.0123 kg of H2
H_2SO_4	1.40	kg	all
Water	7.80	kg	all

Table 2. *Cont.*

Electrowinning			
Flow	**Amount**	**Unit**	**Scenarios**
Output			
Precious metals in anode slime	1	kg	all
Copper cathode	39	kg	all
Nickel	5.49	kg	all

Table 3. LCI table for pressure leaching of anode slimes based on Classen et al. [17] (Part IX, 5.2).

Pressure Leaching			
Flow	**Amount**	**Unit**	**Scenarios**
Input			
Precious metals in anode slime	35.8	kg	all
Electricity	16.2	kWh	all (changed to ROR in SC2)
Natural gas	6.12	MJ	in SC2 adjusted to 0.051 kg of H2
Oxygen	1.87	kg	all
Refinery infrastructure	1.69×10^{-6}	unit	all
Output			
Au, Ag, Pd in intermediate	35.7	kg	all

Table 4. LCI table for Moebius electrolysis based on Classen et al. [17] (Part IX, 5.2).

Moebius Electrolysis			
Flow	**Amount**	**Unit**	**Scenarios**
Input			
Au, Ag, Pd in intermediate	35.7	kg	all
Electricity	16.2	kWh	all (changed to ROR in SC2)
Refinery infrastructure	1.69×10^{-6}	unit	all
Output			
Au, Pd in anode slime	2.82	kg	all
Silver	32.9	kg	all

Table 5. LCI table for Wohlwill electrolysis based on Classen et al. [17] (Part IX, 5.2).

Wohlwill Electrolysis			
Flow	**Amount**	**Unit**	**Scenarios**
Input			
Au, Pd in anode slime	2.82	kg	all
Electricity	16.2	kWh	all (changed to ROR in SC2)
Refinery infrastructure	1.69×10^{-6}	unit	all
Output			
Gold	1	kg	all
Palladium	1.82	kg	all

The LCA was modelled and calculated using the open-source software Brightway2 v.2.5 and the graphical user interface add-on Activity Browser v.2.11.1 [19,20]. For the impact assessment, we used the database ecoinvent cut-off v.3.10. The functional unit is 1 kg of gold. A list of the ecoinvent processes used can be found in Supplement Table S1.

Tables 1–5 show the LCI used by ecoinvent, as well as the adjustments made to account for different scenarios. A detailed description of the scenarios and the underlying assumptions can be found in Section 2.2. In the interest of clarity, flows that are not relevant to CO_2, such as particulate matter or emissions to water, were omitted.

2.2. Scenarios

For this study, four scenarios were developed to evaluate the environmental impact of gold recycling from WEEE under varying process conditions and assumptions, with a focus on identifying opportunities to improve emissions, energy efficiency and resource use. Additionally, inconsistencies in the ecoinvent process were addressed, including the omission of emissions from plastic combustion [17] (Part IX, 5.1.). This was also not included in the work of Bigum et al. [18].

2.2.1. Scenario SC0

Scenario SC0 represents the base case, modeling gold recycling from WEEE following ecoinvent's guidelines but disaggregating it into five distinct process steps. To isolate individual contributions in the gold refining process, we further subdivided it into three subprocesses: pressure leaching, Moebius electrolysis and Wohlwill electrolysis. The electricity consumption and refinery infrastructure were assumed to be equally distributed among the three subprocesses, while natural gas and oxygen were allocated exclusively to pressure leaching.

2.2.2. Scenario SC1

Scenario SC1 is modified to account for CO_2 emissions from the plastic fraction in WEEE and modifies the amount of flux used. In the ecoinvent model, CO_2 emissions from plastics combustion were omitted. In this study, theoretical emissions were estimated based on the stochiometric average carbon content of the plastic fraction, assumed to consist of polyethylene (C_2H_4), polypropylene (C_3H_6) and polystyrene (C_8H_8), with an average carbon content of 88% [21]. According to Classen et al., the WEEE input contains approximately 30% plastics [17] (Part IX, 5.2). The carbon content was estimated by multiplying the plastic carbon content (88%) by the plastic share in WEEE (30%) and the WEEE input required per kilogram of gold [17] (Part IX, 5.2). Based on the principles of stoichiometry, the CO_2 emissions were calculated from the carbon amount by multiplying it with a factor of 3.67. Additionally, the flux (quicklime) amount in ecoinvent, approximately 1.58 kg CaO/kg Cu, was revised [17] (Part IX, Figure 5.13). The study by Sanjuan-Delmás et al. states that in the Rönnskär smelter, quicklime and limestone are used together at 0.142 kg flux/kg Cu [22]. The Rio Tinto Kennecott smelter (USA) reports a value of around 0.03 kg CaO/kg Cu [23]. In a general LCA study on copper production, 0.15 kg CaO/kg Cu was used, which is comparable to the value of Sanjuan-Delmás et al. [22,24]. As a conservative estimate, the highest value of 0.15 kg CaO/kg Cu was adopted for all subsequent scenarios (SC1 to SC3).

2.2.3. Scenario SC2

Scenario SC2 models a transition to renewable energy. Electricity was assumed to come from hydropower, while "green" hydrogen replaced natural gas in the furnaces. The hydrogen demand was calculated using a heat value of 120 MJ/kg, and its production was associated with emissions of 4 kg CO_2eq/kg H_2 [25–27]. Considering Rönnskär's coastal location, offshore wind or tidal energy could also be viable electricity sources. However, the choice of renewable energy source depends on site-specific factors, which vary across refineries. Montanwerke Brixlegg, for example, already use ROR.

2.2.4. Scenario 3 SC3

Scenario 3 SC3 explores the potential for utilizing waste heat from plastic combustion for district heating. The energy content of the plastic fraction was calculated based on the plastics content used in SC1 and the average heating values of polyethylene, polypropylene, and polystyrene, as reported by Huang [28]. To estimate how much heat could be utilized for district heating, the heat needed for the smelting process was first estimated. The specific heat capacities of copper and silica—the major constituents of WEEE aside from plastics—were considered, along with their respective melting enthalpies to calculate the energy demand for smelting the copper. This energy demand was subtracted from the total potential energy content of the plastics, giving the theoretical heat surplus after smelting the copper. An 80% efficiency factor was applied, resulting in a net usable heat of 23.5 MJ (see Table 1 and Supplement Tables S5–S8). This value was used to estimate the CO_2 emissions avoided from natural gas heating based on ecoinvent data (see Supplement Table S1). The calculated emission savings were subsequently subtracted from the total carbon footprint of gold recycling. Note that this calculation is a very simplistic and theoretical approach and can only give a first rough estimate of the district heating potential of WEEE.

2.3. Allocation

In the product system this study is based upon, a total of six products are produced in different process steps: copper, gold, lead, nickel, palladium and silver. In four of the five process steps, more than one product or intermediate is produced (see Tables 1–5). In a multi-output system, environmental impacts have to be allocated to each product or intermediate. The two most common methods used to allocate these impacts in metals and mining systems are calculating the share of the product mass (mass allocation) or calculating the economic value of the product (economic allocation) [29,30]. In the present case, the copper cathode has the highest production volume, with around 1400 kg Cu/kg Au (see Table 6). However, in revenue creation, copper ranks fourth after silver, gold (1 kg) and palladium (1.8 kg Pd/kg Au). In this study's prime example, where base metals such as lead or copper as well as precious metals such as gold or palladium are produced, economic allocation better reflects the reason behind the product system. This is because the precious metal by-products significantly contribute to the revenue of the system. The following table shows the prices used for economic allocation.

Table 6. Product prices used for economic allocation based on the World Bank's pink sheet for the year 2023 [31]. Palladium price is based on (https://macrotrends.net, accessed on 22 February 2025).

Product	Price [USD/kg]	Production Volume [kg/kg Au]
Copper	8.49	1400
Gold	62,500	1
Lead	2.14	94.3
Nickel	21.5	197
Palladium	42,000	1.82
Silver	752	32.9

SKARN Associates provides a comprehensive database that includes information on the energy demand and climate impact of more than three thousand mining assets producing various metals, including gold, copper and nickel [32]. The database uses a special method of impact allocation. According to SKARN, for mines producing gold within a base metal concentrate, all emissions associated with the freight and pyrometallurgic smelting of the concentrate are allocated to the primary metal in that concentrate (e.g., copper). The emissions from the subsequent refining of anode slimes are allocated by economic value. The SKARN allocation method was applied as a third method to the present LCA model.

2.4. Transport

A recurrent theme in the media is how recycling WEEE takes place around the globe and as a result requires global shipping, part of which is illegal [1,33]. In this study, we estimate the impact of the transportation associated with recycling gold from WEEE on climate change. A method similar to the "bee-line measures" employed by ecoinvent was used [17] (Part IX, 5.5). First, the amount of WEEE created by different countries was used to provide masses in tons for each country [1] (Annex 2). Distances were calculated by using the haversine formula, to measure the distance from the capital city of each country to ten major pyrometallurgical refineries (see Supplement Table S2) [34,35].

The total WEEE generation of each country was then multiplied by the distance to the closest refinery to estimate the ton-kilometers (TKM) for each country. Subsequently, each TKM value was multiplied by the CO_2eq per TKM for trucks (0.19 kg CO_2eq/TKM) and container ships (0.010 kg CO_2eq/TKM), based on ecoinvent data v.3.10. It was assumed that 20% of each distance was covered by trucks (16–23 tons, EURO4) and 80% by container ships. This resulted in a total of 7.3 Mt CO_2eq per year for transporting the annual global generation of WEEE to the major smelters, or 0.11 kg CO_2eq per kilogram of WEEE.

It should be noted that the assumption that all WEEE worldwide is transported to refineries likely overestimates the actual situation. However, since the total CO_2eq is normalized by the total scrap amount, this error should not be significant. Also, the real shipping distances are unknown, and it is unlikely that every country exports the total mass of its WEEE (e.g., heavy fractions such as refrigerators) to the nearest WEEE recycling copper smelter.

For the transportation of gold from the refineries to the market, ecoinvent assumes that gold is first transported by truck over a fixed average distance of 250 km to an airport and then distributed to the market via plane. As none of the smelters contacted provided us with primary data, transport had to be approximated. For this, the distance from each refinery to the nearest airport was calculated using Google Earth (https://earth.google.com), accessed on 24. February 2025) (see Supplement Table S3), a tool widely used for estimating the distances for transport processes in LCA [36–38]. Since the exact amount of gold produced from WEEE by each refinery is unknown, an estimate was made based on the refinery capacities (see Supplement Table S2). The total annual amount of gold recovered from WEEE, ≈150 tons, was then distributed proportionally to the capacity of each refinery [39].

The corresponding TKM and the specific CO_2eq for truck transport (based on ecoinvent) were multiplied $\left(TKM \times \frac{CO_2eq}{TKM}\right)$, resulting in a climate impact of 2600 kg CO_2eq, or approximately 0.02 kg CO_2eq per kilogram of gold for the transportation of the annual gold produced from WEEE to the nearest airport. According to Eurocontrol, the average distance of flights was around 1000 km in 2020 [40]. In order to not underestimate this issue, a value of 2000 km was used. This distance, the total amount of gold recovered from WEEE and the specific impact of air transport (0.83 kg CO_2eq/TKM) on climate change from ecoinvent v.3.10 were used to estimate the TKM. The resulting emissions for distributing the gold by air to the market amount to around 250,000 kg CO_2eq per year, or 1.66 kg CO_2eq per kilogram of gold.

3. Results

3.1. The Impact of Quicklime

Figure 1 shows the global warming potential (GWP) of recycling WEEE in Boliden's Rönnskär facility in Sweden by the contribution of conversion, electrowinning, pressure leaching, moebius electrolysis and Wohlwill electrolysis. The figure shows the impact of producing the whole product basket, which consists of 1 kg Au, 1.82 kg Pd, 32.9 kg Ag, 197 kg Ni, 1400 kg Cu and 94.3 kg Pb. The lower bar in the chart labelled quicklime shows the material with the highest contribution to the CO_2eq.

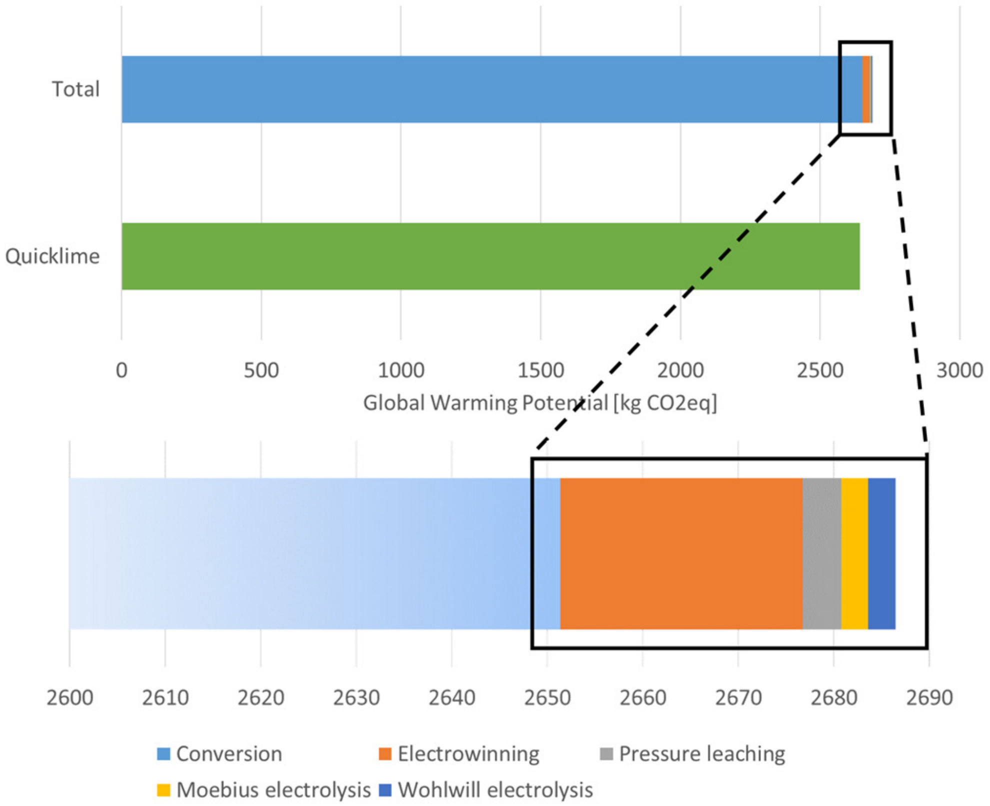

Figure 1. Process contribution of WEEE recycling for the whole product basket in SC0 highlighting the role of quicklime.

The significant effect that quicklime, which is used as flux in the converter, has on the overall impact is notable in Figure 1. This applies in scenario SC0, the base case in ecoinvent, in which the combustion of the plastic in WEEE does not emit CO_2. Including this in our calculation would raise the absolute impact and hence lower the relative contribution of quicklime. Another possible explanation for the high impact of quicklime might be that the amount of quicklime that Classen et al. assumed was used as flux is too high (for more details, see Section 2.2) [17]. As illustrated in the magnified section of the upper bar in Figure 1, the electrowinning of the copper cathodes (SC0) is the second most impactful process after the conversion.

3.2. Different Allocation Models

Figure 2 illustrates the impact of allocation methods on climate change when considering the recycling of WEEE in Boliden's Rönnskär facility in Sweden for the scenario SC1 model. The figure also depicts the difference between primary (ecoinvent v.3.11 cut-off) and secondary productions of the product basket from WEEE (for more details see Supplement Table S4.)

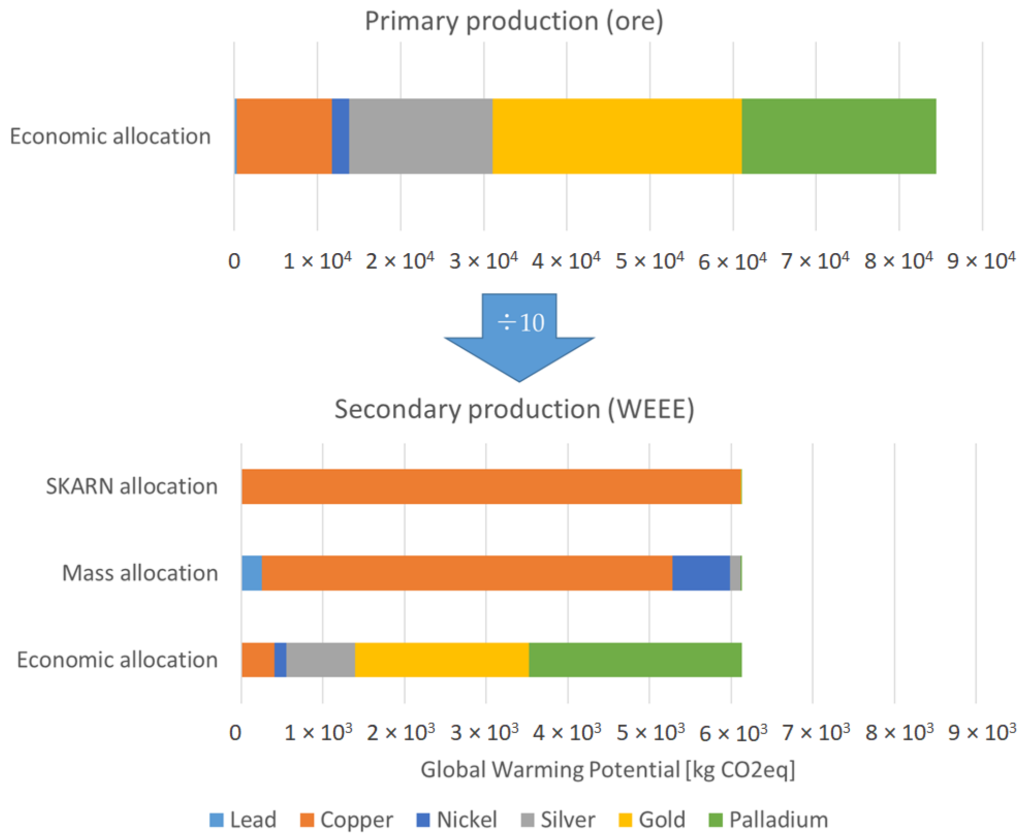

Figure 2. Allocation analysis based on the contribution of each metal to the carbon footprint of the whole product basket and comparing the results to the literature results (Supplement Table S4).

The most striking fact in Figure 2 is the difference in the impact that primary and secondary production have on climate change. If, theoretically, the product basket of WEEE were instead produced from mining (ecoinvent v.3.11. cut-off), the impact would be more than ten times higher. No metal in the product basket could be mined and produced with a lower carbon footprint than that produced through WEEE recycling.

As can be seen from the three bars at the bottom of Figure 2, the impact results obtained when using different allocation methods vary significantly, especially for gold and palladium compared to copper. This is due to the differences in the mass and the market value of these products.

If the prices of the products were not so different or if the environmental impact would scale proportionally to the mass of the product outputs, mass allocation could be useful. Although this is not the case in the present study, the results are shown in the second bar from the bottom.

When allocation is carried out according to SKARN (the bar at the top of Figure 2), copper has the highest impact. This is because the process of copper converting (see Figure 1) has the greatest impact and is only allocated to copper. Only the low-impact process steps of refining the precious metals in the anode slime are economically allocated.

3.3. Scenario Analysis

The scenario analysis results are shown in Figure 3. The graph shows the CO_2eq per kg of gold (economic allocation) for the four scenarios.

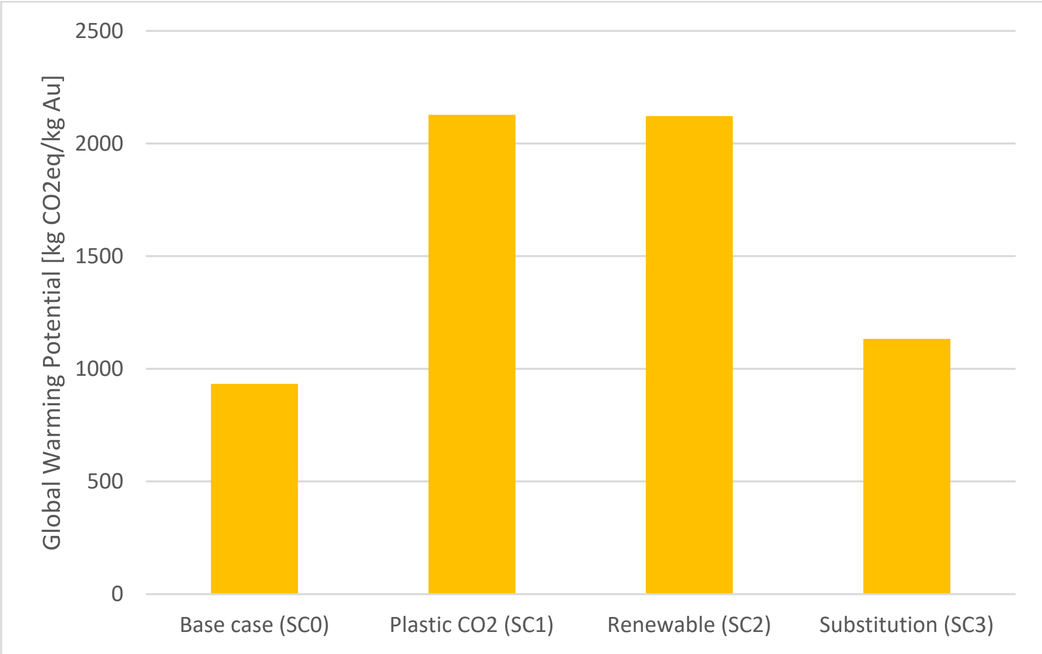

Figure 3. Scenario analysis for the carbon footprint of gold from WEEE in economic allocation.

One interesting finding is the significant impact that omitting the CO_2 emissions has on the results due to the plastic fractions that occur in the WEEE during smelting. This can be seen in the difference between SC0 and SC1, which has more than double the impact on climate change, despite the use of carbon-intensive quicklime being reduced in SC1. In SC1, the contribution of quicklime to the total CO_2eq decreases to around 4%, while the CO_2 emissions generated by plastic combustion have the highest overall impact, at around 95%.

The most striking finding was the marginal difference observed when switching to electricity from run-of-river hydroelectricity (ROR) instead of the Swedish grid mix (see Supplement Table S1), and when using hydrogen instead of natural gas (SC1 vs. SC2). Note that the converter is only fed with the energy from the plastics of the WEEE.

What stands out in Figure 3 is how substituting natural gas heating with the heat of the plastic fraction can significantly lower the carbon footprint (around 50%).

3.4. Transportation Impacts

In all the scenarios considered so far, scrap and gold transportation has been omitted. In the following analysis, an attempt is made to estimate the significance of this process phase (for the method used, see Section 2.4). Table 7 illustrates the contribution of the processes to the total climate impact of producing the whole product basket (SC1) and extending the LCA model by including the results of the transport analysis (see Section 2.4).

Table 7. Analysis estimating the contribution of transport processes to the total carbon footprint (SC1) of producing the metals in the product basket.

Process Step	Amount (SC1) [kg CO_2eq]	Relative [%]
Transport scrap	6.5×10^2	9.63%
Conversion	6.1×10^3	89.8%
Electrowinning	2.5×10^1	0.37%
Pressure leaching	4.1×10^0	0.06%
Moebius electrolysis	2.8×10^0	0.04%
Wohlwill electrolysis	4.5×10^0	0.07%
Transport gold	1.7×10^0	0.02%

Conversion has by far the greatest total impact, while the transport of scrap (and the transport of gold) has only a minimal contribution. The overall impact of the transport processes remains low (around 10%) compared to energy-intensive metallurgical processes.

4. Discussion

This study explores ways to reduce the climate impact of recycling gold from WEEE. We found that recycling gold from WEEE by the most common process route, i.e., the pyro-metallurgical route, has an impact on climate change of around 2000 kg CO_2eq/kg Au. This result depends strongly on the allocation method used.

The recycling of gold from WEEE in a primary copper smelter is a good example of the effect of subjective allocation choices on the results. If the purpose of the integrated copper smelter is to obtain a new raw material input with high metal grades to produce more metals and have a higher revenue, then the environmental impact should probably be allocated on an economic basis. In this case study, the revenue contributed by palladium to the product basket is the highest, followed by gold, silver and then copper. Although the plant is a copper smelter and copper is the material produced in the greatest quantities, a big part of the revenue is generated by the more expensive metals; therefore, the allocation should also follow this economic logic.

In the present case, the CO_2eq is mainly influenced by the fossil carbon bound in the plastic fraction of the WEEE and the energy carrier used. The latter could be improved by switching to renewable energies such as run-of-river electricity and green hydrogen. Meanwhile, for the CO_2eq of plastic combustion, more complex and tedious solutions are needed. To minimize emissions from the plastic fraction of the WEEE, the plastic could be removed prior to smelting in a mechanical or a hydrometallurgical process. However, it would then have to be ensured that the fossil carbon content in these plastic fractions does not end up as CO_2 emissions downstream (unless, e.g., a co-product such as heat production results from waste treatment).

The fact that switching to a renewable scenario does not substantially reduce the impact on the climate (since CO_2 emissions stem from the burning of the fossil carbon in the plastic) has broader implications for the industry. If copper smelters seek to become part of the circular economy (CE) by increasing their WEEE recycling, they will paradoxically increase their carbon footprint. This suggests that limiting WEEE recycling and instead producing copper from primary material using non-fossil energy might be a more promising path to achieving carbon-neutral copper. However, this leads to a conflict of objectives between CE and CO_2 emissions.

In countries where the landfilling of WEEE is not permitted (as in Germany), the WEEE that is not recycled most likely ends up in waste incinerators and releases the same amount of CO_2 emissions as in the pyrometallurgical method, losing large quantities of metal in the process. This would be a fruitful area for further work. A study could compare the system described in this study with an alternative system of disposing the WEEE in household scrap using the existing infrastructure for collecting, sorting and incinerating scrap and then extracting the metals from the fly ash as, for example, Umicore in Hoboken, Belgium does.

The present study has found that district heating is generally an effective means of reducing the carbon footprint of gold from WEEE. When system boundaries are extended to include the provision of waste heat from a WEEE recycling copper smelter to surrounding households using natural gas heating, the carbon footprint of the plant and thus of its products can be reduced by around 50%. The company Aurubis, which supplies heat for around 8000 households in HafenCity East in Germany and plans to significantly expand this by 2025, provides an illustration of what can be accomplished [41].

A final potential means of reducing the CO_2 emissions generated by burning the plastic in WEEE would involve using carbon capture and storage, as exemplified at Amager Bakke in Copenhagen [42,43]. Its success depends on the stored carbon not being released at a later point in time.

All these solutions shift or postpone fossil CO_2 emissions instead of eliminating them. A focus on the producer would open up a more radical solution: namely, not using fossil carbons in EEE in the first place, and instead using plastics derived from biogenic sources. This, of course, comes with its own set of problems (such as the "tank vs. plate debate"), which are outside the scope of this study.

In this study, a theoretical calculation was conducted to demonstrate that the transport of the gold produced from WEEE accounts for approximately 10% of CO_2eq. Additionally, it was shown that the impact of the transport of the final product gold to the market on climate change is insignificant compared to the total CO_2eq from recycling. This is in line with the market for gold in ecoinvent v.3.11 (cut-off), where the total impact of transport is 0.08 kg CO_2eq/kg Au. This initial approximation was rather rudimentary and was based exclusively on secondary data. Further research would be beneficial in this regard to record the flows and distances more accurately, thereby facilitating a more comprehensive understanding of the issue of illegal exports.

This also applies to the district heating scenario, which is based on a very simplistic and theoretical calculation of the net usable heat. This would be a fruitful area for further work that studies thermodynamic modelling and the technical efficiencies in greater depth.

This study, as well as all others to our knowledge, lacks primary industry data. Consequently, future studies should aim to conduct a detailed analysis of on-site data in a copper smelter in a combined LCA model of the primary and secondary routes; this is in order to find further improvements that can reduce the total CO_2 equivalent emissions of copper smelters.

5. Conclusions

WEEE poses significant environmental and health risks if not properly managed. At the same time, it contains economically valuable metals such as gold. Given the environmental and social challenges associated with gold mining, recovering gold from WEEE presents a clear win–win opportunity. However, the industry faces a unique challenge when applying common sustainability strategies.

A major contributor to the carbon footprint of WEEE recycling via the most common route is the combustion of embedded plastics, leading to the emission of approximately 2000 kg CO_2-eq per kg of recovered gold. This is about forty times higher than the carbon footprint of high-value recycling (≈53 kg CO_2eq/kg Au), which supplies nine times the market volume (1350 t Au/a). Since the plastics in WEEE are burned, transitioning to lower-carbon energy sources—one of the standard decarbonization strategies in the smelting industry—has a limited impact. This creates a dilemma: increasing circular economy (CE) efforts while simultaneously reducing CO_2 emissions is counter-productive. A promising strategy to mitigate the climate impact of gold recycling from WEEE is utilizing waste heat from smelters to replace carbon-intensive heating systems in nearby facilities or communities. Further measures include reducing the plastic fraction in input materials, promoting biogenic plastics, or implementing CCS.

Nevertheless, it is important to recognize that the carbon footprint of gold from mining, at approximately 30,000 kg CO_2-eq/kg Au, is more than ten times higher that of current WEEE recycling [12]. Additionally, WEEE presents broader environmental and health risks beyond CO_2 emissions from pyrometallurgical processing. If smelters do not recycle

WEEE, the waste will likely end up in incinerators or landfills, generating similar emissions elsewhere, or be exported to the Global South, where it poses even greater hazards [9,10].

Future policies and pathways must take an integrated approach rather than focusing solely on increasing recycling rates. Sustainable solutions require the coordinated involvement of EEE producers, municipal waste management, smelting infrastructure, global socioeconomic interactions, and consumer behavior regarding usage, repair, and disposal. Only by considering these factors together instead of simply demanding specific recycling rates can a truly sustainable system for WEEE management be achieved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17052086/s1, Table S1. List of ecoinvent processes used in this study; Table S2. List of coordinates of smelters recycling gold from WEEE used for the transportation model; Table S3. List of closest airports to smelters recycling gold from WEEE including distances used for the transportation model; Table S4. Literature values for comparing secondary with primary (mining) production; Table S5. Energy to bring copper to melting point; Table S6. Energy to bring silica to melting point of copper; Table S7. Energy to melt copper; Table S8. Available net energy for district heating.

Author Contributions: The conceptualization of the study was jointly undertaken by B.F. and M.S., with B.F. focusing on the methodology. The LCA database required for the analysis was provided by M.S., while B.F. utilized the software tools for the LCA, the scenario analysis as well as the transport modeling. Validation of the results was carried out by B.F., with guidance and support from M.S. The formal analysis was a collaborative effort between B.F. and M.S., while the investigation, data curation, and resource management were handled by B.F. B.F. also wrote the original draft of the manuscript, while M.S. made significant contributions to the review and editing process. B.F. was responsible for the visualization of the results. Supervision and project administration were carried out by M.S. No external funding was acquired for this project. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

CCS	Carbon Capture and Storage
CE	Circular Economy
CO_2eq	CO_2 equivalent
GLO	Global
GWP	Global Warming Potential
EoL	End of Life
LCA	Lifecycle Assessment
LCI	Lifecycle Inventory
PCB	Printed Circuit Board
ROR	Run-of-river hydroelectricity
RoW	Rest of world
SC	Scenario
TKM	Ton-kilometers
WEEE	Waste Electrical and Electronic Equipment

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5.7. *Synthesis: The carbon footprint of gold*

This chapter synthesizes the findings from all six papers regarding the climate change impact of gold production. Notwithstanding the fact that in a number of the peer-reviewed studies, other impact categories than climate change were discussed, the latter was the most prevalent common denominator. In the following chapter, it is attempted to estimate the impacts on climate change of the annual gold supply, as well as the specific carbon footprint of gold whose origin is unknown. This latter aspect is also referred to as "market datasets" in LCA databases.

The most datasets on climate change are available for gold from industrial mining with gold as the primary metal. The WGC did a literature review in their first issue of "Gold and Climate Change" (WGC 2018). The carbon footprints reported are:

- 11,500 kg CO_2eq/kg Au (Mudd 2007)
- 12,500 kg CO_2eq/kg Au (Nuss and Eckelman 2014)
- 17,000 kg CO_2eq/kg Au (Hagelüken and Meskers 2009)
- 21,000 kg CO_2eq/kg Au (Norgate and Haque 2012)
- 55,000 kg CO_2eq/kg Au (Chen et al. 2018; China only)

The WGC itself states that, based on their expert judgment, they consider a value of 38,100 kg CO_2eq/kg Au to be the most plausible.

In contrast, the CO_2eq for the mining part of the market for gold in ecoinvent v.3.11 totals to around 47,800 kg CO_2eq/kg Au. The relatively high value in ecoinvent presumably stems from the attempt to model the Chinese gold market by adapting the mining dataset from South Africa to better fit China. A practice referred to as IDS (see Paper I).

The SKARN database comprises business analytics data regarding mining and the environment for over 1,700 mining assets and more than 900 companies (SKARN Associates 2025). It contains data for over 400 distinct gold mining assets, including production figures, by-products, type of mining, energy demand, and CO_2eq. The average carbon footprint in the SKARN database (Q4 2023 v.1.0) for mines having gold as their primary product is around 28,900 kg CO_2eq/kg Au for the reference year 2020. This is around 40 % lower than the value reported in ecoinvent v.3.11 for the market for gold. It is important to note that China, the largest gold producer in the world, is currently underestimated in the field of LCA (Newman et al. 2024a). Notably, China is not sufficiently represented in any of the known LCA databases, despite the literature suggesting slightly higher environmental impacts of gold mining in China (Chen et al. 2018; Ulrich et al. 2022). The carbon footprint from the SKARN database will be used for this section's carbon footprint estimation (Table 3), as it is regarded as the most comprehensive source of information on carbon footprints, energy, and water demand in gold mining because of the high amount of data points in the database.

Table 3: Overview of carbon footprints, production volumes, and annual climate change impacts from different gold production routes (rounded values).

Production route	**Carbon footprint [kg CO_2eq/kg Au]**	**Market supply [t]**	**Annual impact on climate change [t CO_2eq/a]**
Industrial gold mining	28,900	3,151	91,400,000
Copper-gold mining	47,000	250	12,000,000
ASM	16,000	520	8,300,000
High-value recycling	53	1,233	65,000
WEEE recycling	2,000	137	300,000
Weighted mean	21,000	-	-
Sum	-	5,300	110,000,000

The SKARN database employs a distinct allocation methodology for base metal mines that produce gold as a by-product, such as copper mines, where the carbon footprint of the smelting process is allocated exclusively to the base metal. Mining and gold refining are allocated by economic allocation. While this approach might seem appropriate for business analytics, it is not commonplace in LCA and must be manually reversed. This can be achieved by calculating the total impacts, including smelting, and subsequently allocating these costs economically between the products. The SKARN database (Q4 2022 v.10) shows that the carbon footprint of gold from copper mines, when utilizing pure economic allocation, is around 47,000 kg CO_2eq/kg Au for the reference year 2020 (Paper II). This is the only available value for gold, a by-product of copper mining that was found during the literature review, and it will thus be used for this section's carbon footprint estimation (see Table 3).

While the figures above represented industrial gold and copper mining, a handful of LCAs have been conducted on ASM in different countries. Valdivia and Ugaya (2011) conducted an LCA on two ASM sites in Peru. One extracts gold from secondary deposits on land, and the other from primary underground deposits. Their study provides inventory data on the use of diesel, water, mercury, explosives, land use, and mined ore, as well as emissions of CO_2, mercury, and tailings. However, data on mercury recovery is limited for both mining sites. The study found a carbon footprint of around 20,000 kg CO_2eq/kg Au for the secondary deposit and around 65,000 kg CO_2eq/kg Au for the primary deposit. Cenia et al. (2018) carried out an LCA on ASM in the Philippines, analyzing four mining sites with distinct processing methods. All sites mine primary underground deposits, with some employing cyanidation either alone or in combination with amalgamation. A notable distinction from other studies is that the authors accounted for the energy demand associated with manual labor as caloric intake, an uncommon approach in LCA that adds significantly to uncertainty and incomparability. Their results obtained for the four different processes range from 4,000 kg CO_2eq/kg Au (cyanidation and amalgamation) to 50,000 kg CO_2eq/kg Au (cyanidation with carbon-in-leach). The LCA on ASM performed by Kahhat et al. (2019) in Peru examines six types of mining operations extracting gold from secondary deposits using amalgamation. Their study includes LCI data on diesel, water, land use, and mercury, including recovery through retorts. The results for the six different processes vary between 10,000 kg CO_2eq/kg Au (river dredging) and 20,000 kg CO_2eq/kg Au (secondary deposit). It should be noted that in order to facilitate greater comparability with the other studies under discussion in this section, the potential biogenic CO_2eq from deforestation assessed by Kahhat et al. has been excluded. Cano-Londoño et al. (2023) report results ranging from 170 kg CO_2eq/kg Au to 15,000 kg CO_2eq/kg Au, but these are associated with formalized ASM using processes without mercury and with access to the electricity grid and thus represent a special case rather than the norm. In Paper III of the present cumulative dissertation, primary in situ data for gold from ASM with more than 100 data samplings were collected in several expeditions in the Brazilian Amazon rainforest. For the most common processing technique for alluvial mining, which involves the use of a sluice box, pumps, excavators, and mercury, the average carbon footprint of 28 mining sites is around 19,000 kg CO_2eq/kg Au (arithmetic mean). The arithmetic mean of the four different mining techniques for ASM analyzed in the Brazilian Amazon rainforest is ≈16,000 kg CO_2eq/kg Au. This value is regarded as the most comprehensive dataset, given the highest sample size compared to the other studies. Therefore, it will be used for this section's carbon footprint estimation (see Table 3).

Having discussed mining in the sections above, the following two sections will focus on recycling. For gold from high-value recycling, the only detailed LCA containing LCI tables identified in the course of research for the present thesis can be found in Paper IV. The study found that the carbon footprint is approximately 53 kg CO_2eq/kg Au. It is important to note that this estimation is based on a limited number of state-of-the-art recycling plants in Germany and assumes that no newly mined feedstock is accepted. In a subsequent LCA commissioned by one of the aforementioned recycling plants, the carbon footprint was estimated to be 36 to 43 kg CO_2eq/kg Au, contingent on the form of the final gold product (C. Hafner, Schmidt, and Fritz 2022; Schmidt, Heinrich, and Huensche 2024). For the present estimation of the carbon footprint here, the higher value of ≈53 kg CO_2eq/kg Au from Paper IV was utilized (see Table 3) to ensure a conservative estimate and avoid overestimating the results.

The literature values for gold derived from WEEE recycling via the most common route, which employs the pyrometallurgical infrastructure of copper smelters, exhibit significant variability. The study by He et al. (2023) reports a value of 5,840 kg CO_2eq/kg Au, yet lacks LCI data and is therefore challenging to comprehend. The study by Rezaee et al. (2023) compares several hydrometallurgical methods for WEEE recycling, excluding a provision of their results per kilogram of gold. Li et al. (2019) present a significantly higher carbon footprint for the pyrometallurgical recycling of 57,900 kg CO_2eq/kg Au compared to the other studies. This is presumably because they are not using the cut-off model, and thus the scrap input has environmental burdens (see section 3.2), which is different from the other studies reviewed. Ecoinvent v.3.11 states that the value is ≈953 kg CO_2eq/kg Au for their dataset representing the global situation (Rest of World, RoW), but it excludes the CO_2 emissions occurring from burning the plastic fraction inherent in the WEEE input (Classen et al. 2009; Wernet et al. 2016). Besides this error, the ecoinvent data report by Classen et al. (2009) is the only study that provides LCI data including process details and their sources used. Following the attempt to correct the errors in the ecoinvent process, a carbon footprint of ≈2,000 kg CO_2eq/kg Au was estimated in Paper VI. Due to the points discussed above, the latter was selected for the present carbon footprint calculation (see Table 3), as it is regarded as the most comprehensible value.

A general problem encountered in this cumulative thesis was the gold industry's discretion, making it difficult to obtain comprehensive numbers such as production volumes from mining and recycling. The discretion of the Swiss refineries (refining ≈60 % of the annual gold production in 2018) and the Chinese gold industry (≈10 % of annual gold production in 2022) alone contributes significantly to the limited traceability of the gold supply chain (Gomez 2024; Mbiyavanga 2019; Newman et al. 2024b; Ulrich et al. 2022).

The following section delineates a methodology for approximating the volumes for each of the gold routes. The methodology described here follows the one explained in Paper I and updates the values used back then (2021). This methodology was subsequently employed to estimate the total impacts on climate change from the annual gold supply as well as the specific carbon footprint of generic gold from the market (see Table 3). The total production from industrial gold mining was estimated using the mine production of 3,661 t/a for the reference year of 2024 from WGC (2025a). It was assumed that this number contains gold from copper mining and ASM. A global gold production from ASM of 520 t/a (Cheng et al. 2023) was used, of which half was assumed to be included in the WGC statistic. Consequently, 260 t/a were deducted from the aforementioned 3,661 t/a. According to Schütte et al. (2023), the arithmetic mean of the gold production from copper mining for the years 2018 to 2021 was around 232 t/a. It is further stated that this estimation is based on mining data covering 72 % of the global gold production. Therefore, a slightly higher value of 250 t/a was assumed for gold from copper mining, which was also subtracted from the aforementioned 3,661 t/a. According to the WGC, the total production from recycling in the reference year of 2024 was 1,370 t/a (WGC 2025a). Hewitt et al. (2015) state that the shares of gold recycling from high-value material versus WEEE are 90 % and 10 % respectively. The final estimation of the total impacts on climate change from the annual gold supply as well as the specific carbon footprint of generic gold from the market can be found in Table 3.

From Table 3 it can be seen that industrial gold mining has been identified as the activity with the highest annual impact on climate change, primarily due to its relatively high specific carbon footprint and substantial production volume. Interestingly, the second-highest annual CO_2eq are from gold associated with copper mining, despite the relatively low production volume due to the highest specific carbon footprint. In contrast, high-value recycling emerges as the least impactful on climate change, despite the relatively high production volume ranking second to mining. However, it is important to note that this is only true for recycling plants that do not accept newly mined feedstock (see section 3.2). Dividing the total annual impacts on climate change by the total annual production (last row) results in a carbon footprint for gold from the generic market of around 21,000 kg CO_2eq/kg Au. This figure is over 50 % lower than that of the gold market in ecoinvent v.3.11 (48,000 kg CO_2eq/kg Au).

A comparison of the total annual emissions from gold production of ≈110 Mt CO_2eq/a (Table 3) with those of steel with ≈2.8 Gt CO_2eq/a, aluminum with ≈1.1 Gt CO_2eq/a, and copper with 97 Mt CO_2eq/a can be seen in Figure 15 (International Aluminium 2023; International Copper Association 2023; Lei et al. 2023; World Steel Association 2024).

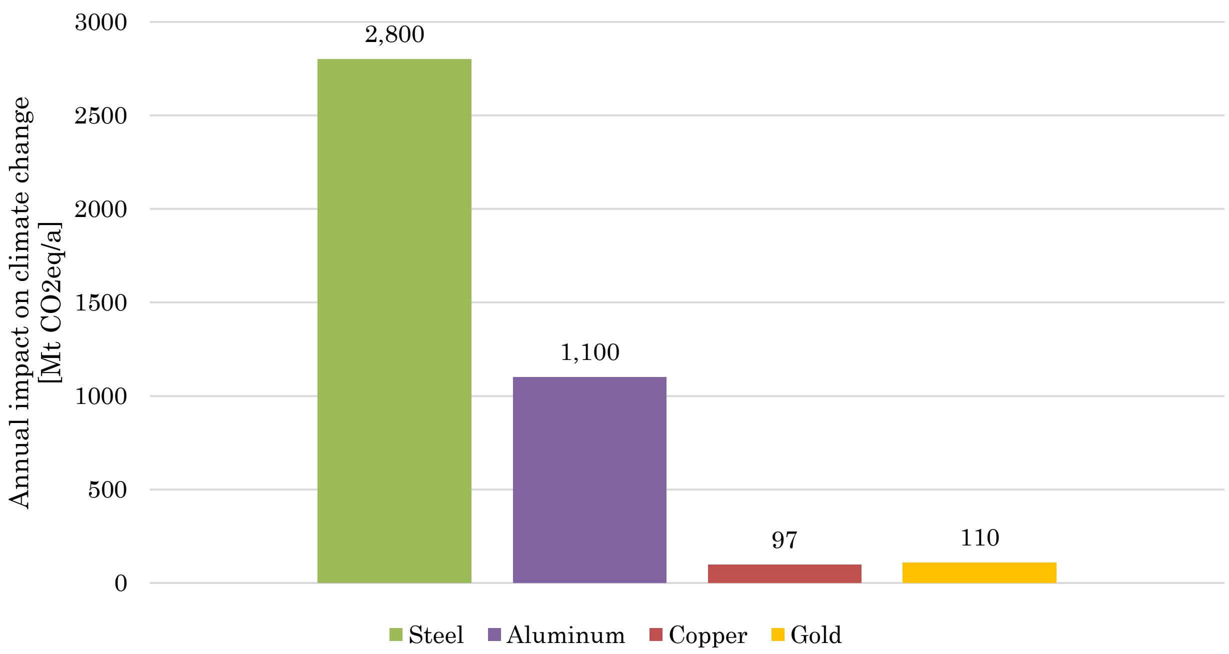


Figure 15: Annual impacts on climate change by different base metals in comparison to gold.

The chart shows that gold production has a comparatively insignificant impact on climate change compared to steel and aluminum, but its impacts are comparable to those of copper. The latter is noteworthy, as copper is a widely utilized base metal with a diverse range of technological applications, whereas gold is a precious metal predominantly employed for fashion and investment purposes.

6. Discussion

6.1. Gold in LCA databases

As demonstrated in Paper I, common LCA databases, like Sphera (formerly GaBi) and ecoinvent, are omitting important gold production routes and making assumptions between mines in different regions within their regional datasets. This is called intersystemic data scaling (IDS). Furthermore, an estimation was made that the gold market (reference year 2018) consists of ≈60 % gold derived from mining with cyanidation, ≈22 % from high-value gold recycling, ≈9 % from ASM, ≈7 % from copper mining, and ≈2 % from the recycling of WEEE. Figure 16 provides a simplified overview of the main results reported in Paper I.

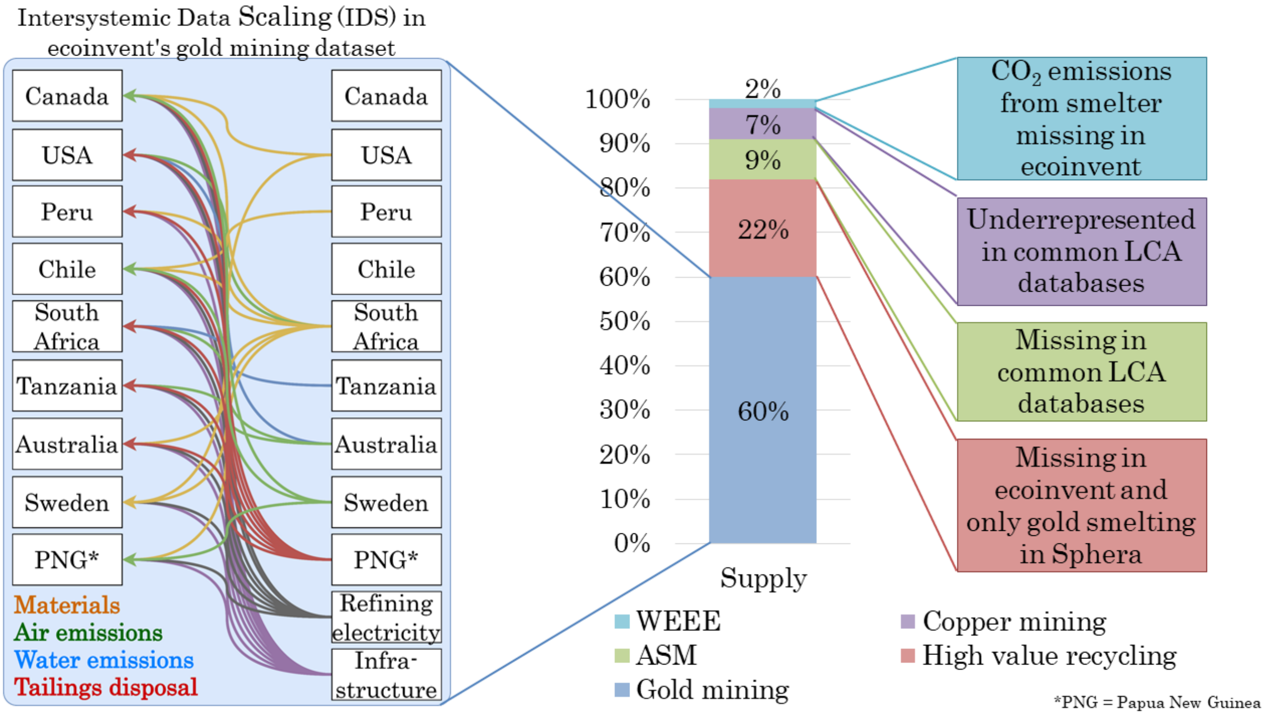


Figure 16: Visualization of the main findings from Paper I.

It could be argued that the results of this review study are the rule rather than the exception in LCA. It is widely acknowledged that model assumptions can introduce uncertainty into LCA studies (Huijbregts 1998). But in the context of gold, the uncertainty is likely to be exacerbated by emphasis on regionalization over other geological or technical characteristics of mines. This approach leads to the extrapolation of data between mines with different deposits and mining techniques (IDS).

According to Pauer et al. (2020), the two most widely used LCA databases are Sphera (formerly GaBi) and ecoinvent. A potential limitation of Paper I lies in a stronger focus on the ecoinvent database for the detailed analysis of gold datasets due to the fact that the Sphera (formerly GaBi) database only publishes limited information in addition to the LCA results concerning the input data for the models and is hence less comprehensible (Guo et al. 2025). Please note that, shortly prior to the submission of this thesis, in March 2025, the LCA dataset for high-value recycling of gold generated in the present thesis (Paper IV) was added to the LCA database Sphera (formerly GaBi); due to timing, this update could not be reflected in the present work.

Doubts could be raised about the feasibility of including ASM data in LCA datasets, as this sector is highly informal and unregulated; thus, collecting reliable data is fairly complex. While acknowledging these concerns, it is assumed that incorporating this activity is highly relevant. This is due to different processes and thus environmental impacts compared to industrial gold mining, such as ecotoxicity from mercury emission. The incorporation of ASM data could initially serve as preliminary and conservative estimates, which can be subsequently refined and updated as more comprehensive data becomes available.

The results of Paper I have implications regarding the topic of uncertainty in LCA. This topic has been debated in the LCA community since the 1990s, and even today there is still no consensus, as Heijungs shows in his (2024) work *Probability, Statistics and Life Cycle Assessment*. Numerous approaches to quantifying uncertainty in LCA have been proposed, including pedigree matrices, fuzzy data sets, analytical uncertainty propagation (Taylor series), Monte Carlo simulations, and Bayesian statistics (Heijungs 2024; Rosenbaum et al. 2018). Paper I deals with assumptions and methodological decisions that significantly increase the qualitative and systematic uncertainty of LCA models. The methods discussed in section 3.3 and by Heijungs (2024) for determining parameter uncertainty do not adequately capture any of the systematic uncertainties identified in Paper I.

Critics may point out that the present dissertation is missing a comprehensive study on industrial gold mining. However, this particular route was covered in extensive literature research during the course of this dissertation. A review of the literature revealed the existence of numerous LCA studies conducted in various countries, including those by Chen et al. (2018), Kadivar, Akbari, and Vahidi (2024), Konaré et al. (2024), Mudd (2007), Norgate and Haque (2012), and Ulrich et al. (2022). Additionally, the WGC published five reports specifically on the topic of climate change in their series "Gold and Climate," wherein they, inter alia, reviewed different LCAs and carbon footprints of gold mining (WGC 2018, 2019, 2020, 2021, 2022). Moreover, the SKARN database contains data on energy, water, and climate change for more than 500 gold mining assets. Furthermore, as discussed in Paper I, LCA data for gold from mining can be found in the most common LCA databases, Sphera (formerly GaBi) and ecoinvent. It is thus believed that the LCA data for gold from industrial mining, particularly with regard to water, energy and climate change, is the most thoroughly researched production route, while this dissertation emphasized other, less researched routes.

Despite the identification of significant issues in the LCA datasets for gold shown within this dissertation, the utilization of these datasets is not to be discouraged. Particularly in cases where acquiring primary data from a specific gold producer is not feasible, using these datasets appears to be the best solution. In such cases, the datasets still remain valuable for preliminary estimations. If initial findings indicate that gold contributes significantly to the overall environmental impacts of the study, it is recommended that a more thorough examination and, if possible, refinement of the LCA data be carried out.

6.2. Gold from copper-gold mining and multi-product allocation

The extraction of gold as a by-product from copper mining is a significant aspect of the global gold supply, accounting for approximately 10 % of the total output. The complexity of such multi-product processes poses challenges for LCA, particularly in terms of allocating environmental impacts to each product and process involved. The results of Paper II indicate that the prioritization of allocation methods as suggested by ISO 14044 may not always be the most suitable approach and does not accurately represent the benefit of the product system. Figure 17 provides a simplified overview of the main results reported in Paper II.

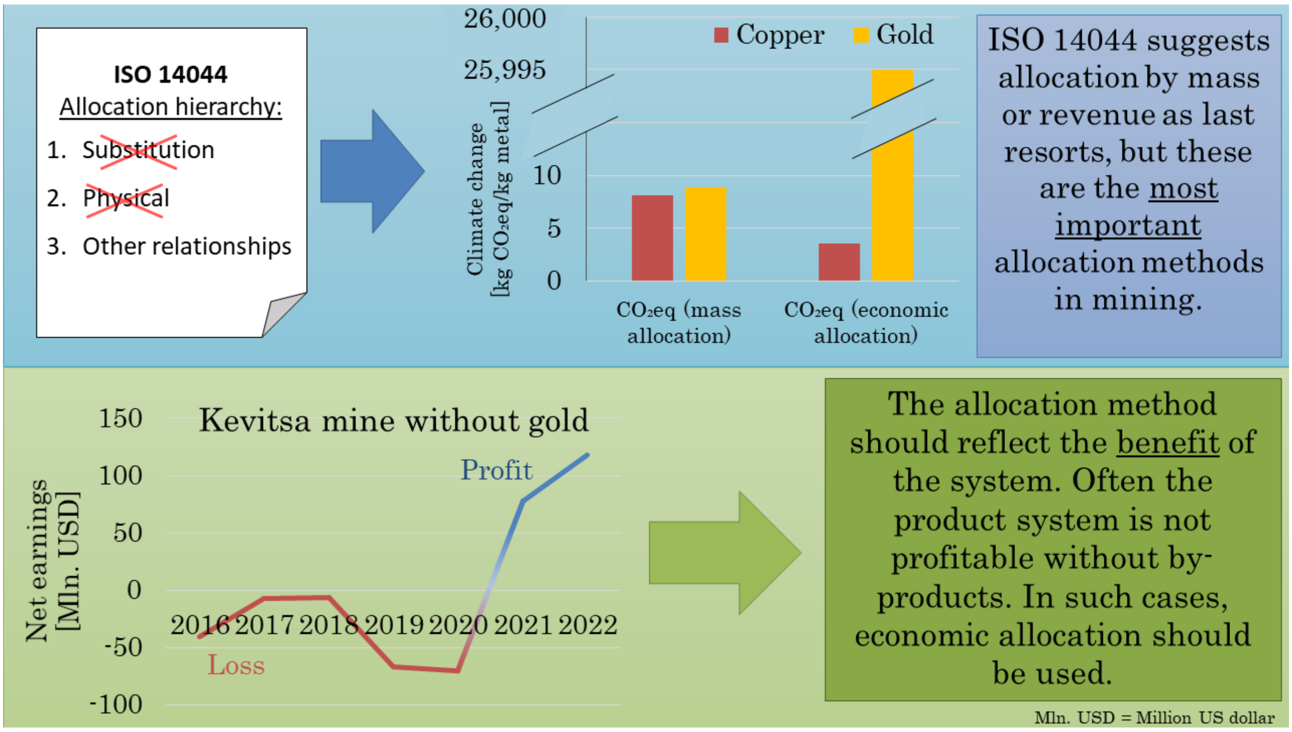


Figure 17: Visualization of the main findings from Paper II.

The present work comes to the conclusion that in many cases economic allocation is a good choice. It is possible that this result may underestimate the role of price volatility. It is correct that prices do fluctuate and that this has impacts on the environmental impacts when economic allocation is used. But Paper II showed that the production volumes in a multi-product process will fluctuate per year, as will the prices of the products. Moreover, the model used to discuss price fluctuations assumes a ceteris paribus scenario where all the other parameters stay unchanged besides the prices. In reality, when prices are changing, this also affects the markets and the industry and thus the environmental impacts of their products. This can be seen from gold mines closing when prices are lower and then reopening when the prices are rising (Laurence 2006).

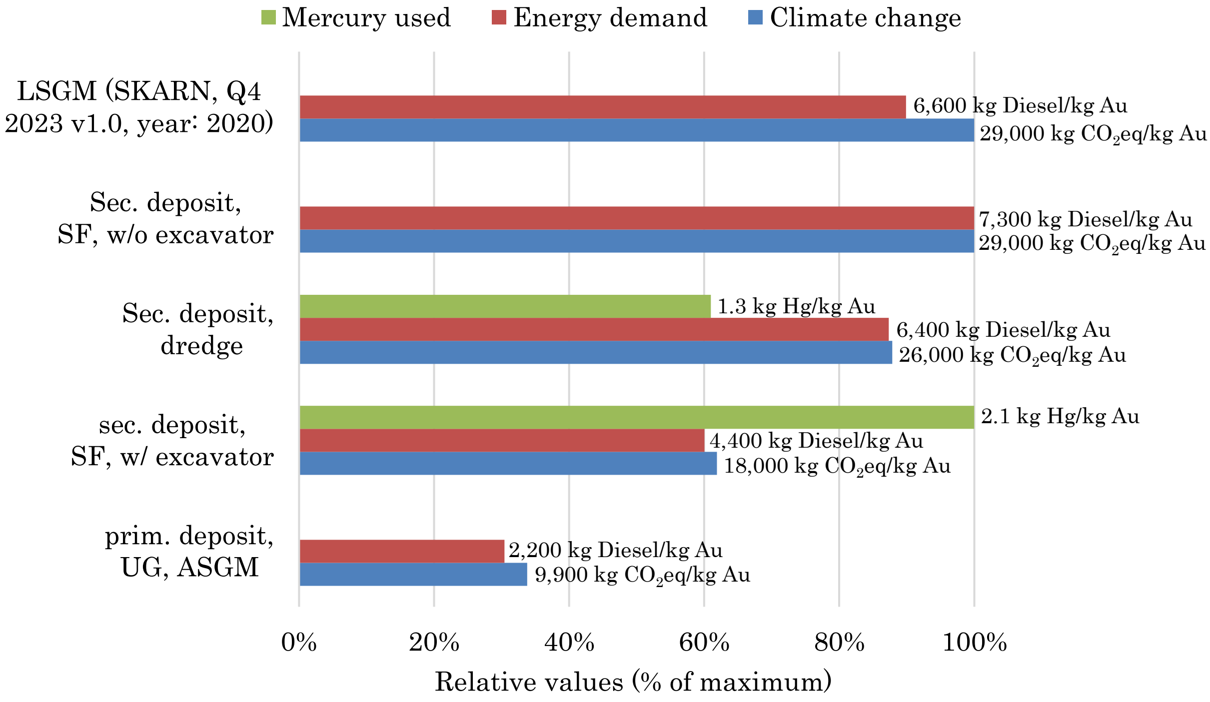
The findings of this study may be somewhat limited by the exclusion of other allocation methods besides the ones explicitly discussed in the ISO 14044, such as the normalized mass-based approach, allocation by entropy (scarcity), or production costs (Lai et al. 2021; Torrubia, Valero, and Valero 2023; Tuusjärvi, Vuori, and Mäenpää 2012). These methods are proposed, among other things, to eliminate the subjective and temporary social relationships that prices represent (Torrubia et al. 2023; Tuusjärvi et al. 2012). Paper II explains how these alternatives, at least to some extent, are also affected by prices. This is because the choice of products that a mine decides to extract from a deposit is already based on prices. And this choice of products determines the multi-product allocation. Cadmium, for instance, was previously regarded as a hazardous substance in the context of zinc mining. However, it is now regarded as a valuable commodity for the energy transition, particularly in the fields of batteries and photovoltaics. The crustal abundance of cadmium remained constant, but its application and subsequent demand have increased, driven by economic considerations (Werner et al. 2024). It is assumed that the fundamental objective of mining operations is to generate profit, and consequently, the allocation method should align with this objective. Furthermore, the question can be raised as to whether the scarcity of resources (needed e.g., for entropy) might be reflected, at least in part, by higher prices (Popp et al. 2018).

Notwithstanding the identification and emphasis on contemporary issues in allocation methods, a conspicuous deficiency in Paper II lies in the absence of proposing a specific alternative allocation method. Although this may be correct, the paper has scientific merit. Paper II should be considered a case study that uses copper-gold mining as a primary example to examine prevailing allocation approaches and to highlight common challenges associated with them. One of the key findings is that allocation rules in LCA should place greater emphasis on the benefits provided by the product system rather than relying strictly on allocation criteria derived from natural laws.

The discussion on uncertainty, as already presented in Section 6.1 regarding Paper I, is also highly relevant for Paper II. Numerous methods for quantifying uncertainty in LCA have been proposed by the LCA community, such as pedigree matrices, fuzzy data sets, analytical uncertainty propagation (Taylor series), Monte Carlo simulations, and Bayesian approaches (Heijungs 2024; Rosenbaum et al. 2018). Paper II deals with assumptions and methodological decisions that significantly increase the systematic uncertainty of LCA models. None of the aforementioned methods for quantifying parameter uncertainty in LCA adequately reflect the systematic uncertainties identified in section 3.3 of Paper II.

6.3. Gold from ASM

Expeditions conducted in Paper III across more than 47 ASM sites in the Tapajos region of the Brazilian Amazon rainforest revealed that mercury emissions are significant, even though retorts are used, and that the energy demand and its associated CO_2eq are comparable to those of industrial mining. The bar chart below (Figure 18) compares some of the main results from Paper III as relative values normalized to each category's maximum. Surface mining of secondary deposits without an excavator (sec. deposit, SF, w/o excavator) has become very rare in the Tapajós region, and hence we were not able to collect data on mercury use (see Figure 18).



LSGM = large scale mining; Sec. = secondary; SF = surface; w/ = with; w/o = without

Figure 18: Visualization of the main findings from Paper III. Normalized to category maxima (% of maximum).

A notable limitation of the study is its restriction to the Tapajos area within the Brazilian Amazon rainforest. The study area exhibited a variety of extraction techniques that are used in the same or very similar ways around the world (Massaro and de Theije 2018; Priester et al. 1993; de Theije and Heemskerk 2009). It is assumed that the observed patterns of gold mining in the Tapajos region are indicative of the potential for gold mining to develop in other regions of the world, particularly the mechanization trends (Caballero Espejo et al. 2018; Massaro and de Theije 2018). Additionally, studies have documented the use of retorts in other regions, further supporting the potential for cross-country comparisons (Bosse Jønsson, Charles, and Kalvig 2013; Kiefer et al. 2015; Spiegel et al. 2006). In light of these findings, it is presumed that the analysis holds relevance for the application of ASM in other regions as well.

The findings of our study may be subject to the Hawthorne effect, as the behavior of the individuals within the mines may be influenced by the presence of environmental scientists (Diaper 1990). Possibly the results are an outcome of the subjects becoming aware of the research and taking measures to alter their behavior. While the possibility of these factors influencing the outcomes cannot be discounted, the likelihood appears low. Practices were witnessed that fell short of optimal standards in ASM, including the open burning of the amalgam and thus breathing the hazardous fumes without proper personal protection. Another alarming practice observed was biting on larger amalgamated particles to determine by hardness whether it could be gold. Moreover, once mercury is in the process until its final separation from the gold, losing mercury means losing gold. Finally, even if the findings were artificially manipulated, the ultimate results indicate that the energy demand and mercury losses remain excessively high and necessitate reduction.

Another shortcoming of this research is its focus on energy demand, climate change, and mercury emissions while not researching other environmental impacts of ASM, such as deforestation, biodiversity loss, or human toxicity. Due to the constraints imposed by the time and resources available for data collection in the remote ASM sites of the Tapajos region, the study design was focused on a limited number of issues. Mercury was selected as a focal point due to its prevalence in ASM research literature (Berzas Nevado et al. 2010; Cheng et al. 2023; Reuther 1994). The topic of energy demand and its associated impacts on climate change is of particular importance in the field of metals and mining (Lèbre et al. 2020; Norgate and Haque 2010; Vidal, Goffé, and Arndt 2013). Additionally, as described by Rosenbaum (2018), the impact category of CO_2eq is regarded as fairly certain, while others, such as human toxicity, are not (see section 3.2). Although this study does not cover all possible dimensions of the environmental impacts of ASM, it fills an important gap in the literature by providing new empirical evidence on energy demand, climate change, and mercury emissions.

The results of this study may be somewhat limited by measurement errors and uncertainty. The loss and recovery of mercury was measured 47 times independently and in situ. All the data on the measurements is publicly available in the appendix of Paper III (see section A3). The precision of the balances used (± 0.1 g) for the mass-balance methodology is assumed to be significantly lower than the natural variability of the dataset itself. This variability can be explained by many factors, such as differences in ore grades, processing techniques, or individual preferences of the miners. The data on the energy consumption for gold in ASM was based on process-specific data collected for 34 different mines by conducting information-oriented interviews with complementary observations and looking into the accounts of the mine owners. Again, all the data was published. Most of the figures are used by the interviewees to calculate profits and losses. It is believed that the interviewees do their best to keep this error rather low, as otherwise, they might risk losing money. It is thus assumed that the natural variability of the energy demand in mining is higher than the error of each individual data point. For the calculation of the carbon footprints for gold from ASM, secondary data was used to calculate the CO_2eq based on the carbon content. The error resulting from this calculation is estimated to be minimal, as the mechanism of the effect of fuel combustion on greenhouse gases is well understood and the impact category of CO_2eq is, as mentioned above, regarded as fairly certain (Rosenbaum et al. 2018). Critics may point out that the conversion factor between sponge gold and fine gold was estimated using primary data collected at different times and locations, rather than being determined specifically for each in situ measurement. Only the weight of the sponge gold prior to fine gold refinement was specifically measured in situ for each data point. It is possible that the gold grade of the sponge gold content is fluctuating, influencing the final results. However, the significance of this potential error is likely minimal because, as mentioned above, the amounts of diesel and mercury utilized are presumably themselves subject to fluctuations due to natural variability in ASM.

6.4. Gold from high-value recycling

High-value recycling of gold scrap, e.g., coins or old jewelry, is contributing to around 90 % of the global annual gold recycling and ranks second after gold mining in terms of annual gold supply. Paper IV collected primary data in high-value gold recycling plants to assess the environmental impacts of this process. The study found that the impacts are significantly lower compared to all other gold production routes (see Figure 19). In Paper V, a sensitivity and scenario analysis revealed ways to further reduce the environmental impacts of high-value gold recycling and found that the impact contribution by transport processes is insignificant compared to the overall results.

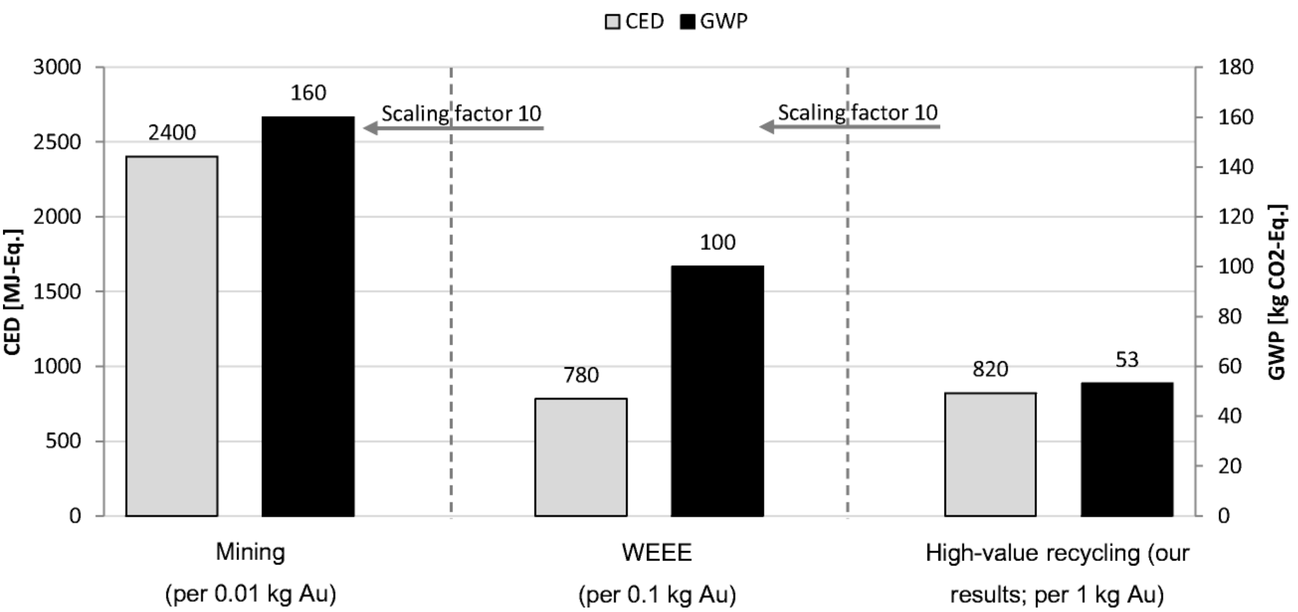


Figure 19: Visualization of the main findings from Paper IV based on Fritz et al. (2020). Note: values scaled down by factor 10 for WEEE recycling and by 100 for mining.

An important point of concern is the definition of the feedstock and the choice of the allocation method. In this dissertation, the terms "high-value gold scrap" and "recycling" are used. A significant discourse is currently unfolding within the jewelry industry concerning the nomenclature of the inputs to gold recycling plants, such as old jewelry and coins (Espinosa 2025; International Organization for Standardization 2025; Precious Metals Impact Forum 2022). The main question is whether these items should be designated as scrap, given that they are not being discarded as waste. This prompts a reexamination of the term "recycling," which is commonly understood to apply only to waste materials. Consequently, alternative terms such as "repurposing" or "reprocessing" have been put forth (Espinosa 2025). The implications of redefining "waste" and "recycling" extend to the methodology of the LCA, particularly the "cut-off" approach. In the context of this research, the cut-off approach was employed, inter alia, due to the fact that the recycling plants providing the primary data for this dissertation do not accept newly mined material. More details on this discussion can be found in section 3.2.

The selection of the cut-off approach is closely related to the allegation that its implementation in high-value recycling could lead to greenwashing by falsely declaring newly mined material as waste. However, a significant proportion of newly mined material would be deemed unsuitable for aqua regia processes used by the recycling facilities examined in this study. Consequently, the newly mined material would require refinement prior to its designation as waste. While this theoretical possibility exists, ensuring that the material is, in fact, EOL is imperative. In the present dissertation it is claimed that the crux of this issue lies not in the ambiguity of recycling definitions but rather in the traceability and transparency of the gold supply chain.

It is crucial to exercise caution when interpreting the results, as they are based exclusively on data from state-of-the-art recycling plants in Germany. The results of this study are representative case studies for producing gold from high-value scrap with aqua regia in state-of-the-art recycling plants in Germany. The extent to which these findings can be generalized is limited by the focus on a few recycling plants; data from additional case studies in other facilities are currently lacking. It is conceivable that the outcomes might vary for older recycling facilities or in other regions, or both. However, given the high gold content in the feedstock and the well-known and simple aqua regia process, it can be assumed that the differences in the specific environmental impacts in less developed plants are not likely to be significantly higher elsewhere.

The improvements of the environmental performance identified in Paper V may be somewhat limited by the fact that they have not been tested for technical and economic feasibility and are therefore rather unrealistic for the near future. The economic viability of substituting natural gas heating with "green" hydrogen is yet to be determined. The implementation of using less carbon-intensive energy sources such as wind, river, and photovoltaic energy may not be viable in the near term. This is primarily due to the fact that the recycling plants in question are small industry plants located in close proximity to urban areas, where the implementation of an autonomous energy supply through photovoltaic and wind turbines may encounter significant challenges. And the decarbonization of the energy mixes is in many countries progressing slowly or encountering challenges in ensuring a reliable and sufficient energy supply at all times. Notwithstanding the study's findings, derived from the application of prospective LCA methodologies, are noteworthy. However, it is imperative to acknowledge that the results should be regarded as a best-case future scenario.

It could be argued that the results are less reliable, as a quantitative uncertainty analysis was not included in Papers IV and V. Although a typical uncertainty analysis in LCA, like Monte Carlo simulation, would have been possible for this study, as the background LCI data relies on ecoinvent, it was decided against it. This is mainly due to the subjective and irreproducible character of the pedigree matrix approach used by ecoinvent in the background that is under much debate. Just recently it was criticized to be "completely wrong" by Heijungs (2024:24). This is why no quantitative uncertainty analysis was included in the LCAs for gold production from high-value scrap in Paper IV and V (see section 3.3). In the following paragraph, it is attempted to briefly discuss this topic qualitatively. The LCA results are based on primary, process-specific in- and output data for three different recycling plants. The data was mainly based on annual consumption figures from the procurement department and the emission measurements from the operation managers. It is assumed that the error in the procurement figures is rather low, as having these numbers incorrect would mean losing money for the company. The error of the emissions measurements is also assumed to be low, as this is done in standardized ways by professional independent personnel. Another factor impacting the uncertainty of the results of Papers IV and V is the different impact categories and their underlying impact methods. The midpoint impact categories and their results are varying in their certainty based on the impact method used. CO_2eq, for instance, is regarded as fairly certain, whiles others such as human toxicity, are less certain (Rosenbaum et al. 2018). It was attempted to reduce this error by the development of a methodology in Paper IV to choose the impact categories most relevant for metal production and regarded as most reliable by the EU. Based on the qualitative analysis above, it can be stated with a high degree of certainty that gold from high-value recycling (with cut-off) has lower environmental impacts than gold from WEEE recycling and mining in most of the impact categories examined (see Figure 19).

6.5. *Gold from WEEE recycling*

Paper VI disclosed that the incineration of the plastic fraction in WEEE has a substantial impact on climate change from pyrometallurgical WEEE recycling. A scenario analysis revealed that this is resulting in a situation where typical decarbonization strategies of the smelting industry fail. For this reason, alternative scenarios, such as district heating, carbon capture and storage (CCS), and bioplastics, have been discussed. Figure 20 provides a simplified overview of the main results reported in Paper VI.

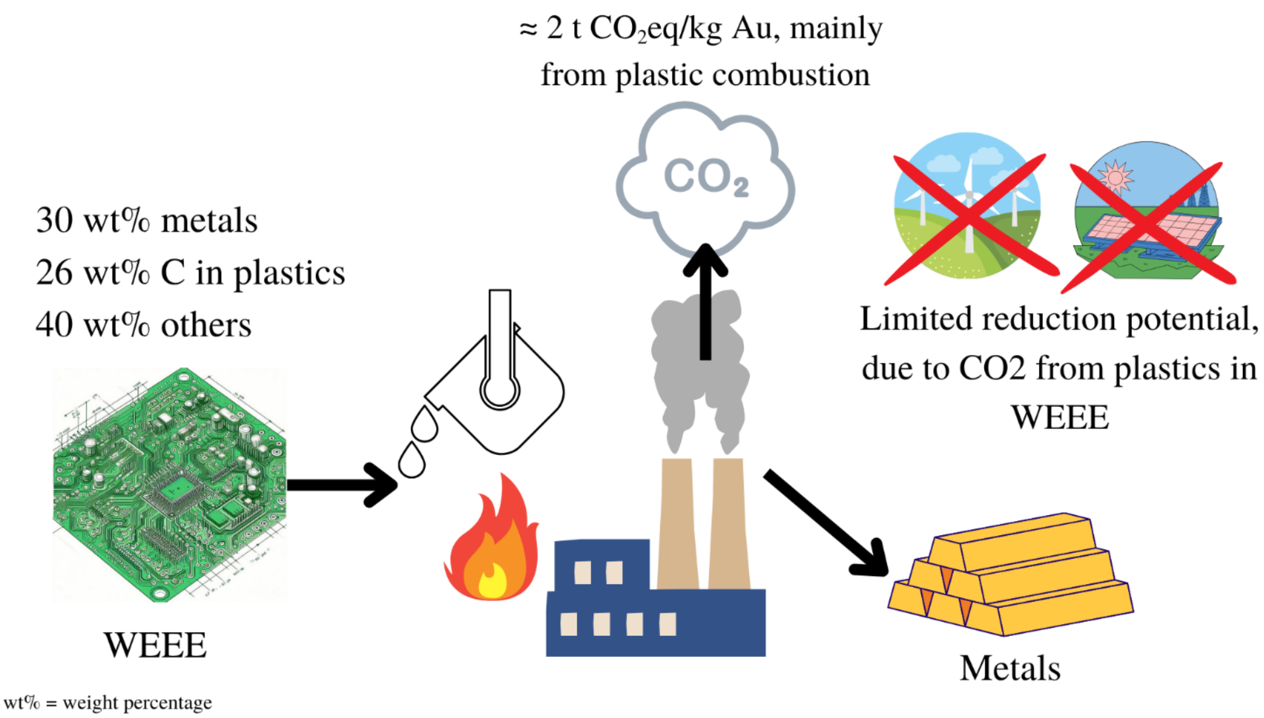


Figure 20: Visualization of the main findings from Paper VI.

The availability and quality of primary data in Paper VI were limited, requiring reliance on secondary data. Contact was initiated with prominent smelters accepting WEEE as feedstock; however, none were willing to provide unpublished data for an LCI. Thus, the LCI employed in this study is derived from the background data for ecoinvent, as documented by Classen et al. (2009:Part IX), which is characterized by its comprehensible presentation. Relying on secondary data only has implications for the uncertainty of the LCA results, which is assumed to be rather high. Although a typical uncertainty analysis in LCA, like Monte Carlo simulation, would have been possible in Paper VI, as most of the LCI data relies on ecoinvent, it was decided against it. This is mainly due to the subjective and irreproducible character of the pedigree matrix approach used by ecoinvent that is under much debate (see section 3.3). Just recently it was criticized to be "completely wrong" by Heijungs (2024:24). Nevertheless, it can be stated with a high degree of certainty that the key result of the study—the high contribution of the plastics embedded in the WEEE to the overall impacts on climate change—is robust against the uncertainties.

A notable limitation of Paper VI is its exclusive emphasis on the LCA impact category of climate change, while other crucial categories such as particulate matter and abiotic depletion are omitted. This focus was chosen because the smelting industry recognizes its important challenges and opportunities in the area of CE and decarbonization (Aurubis AG 2024; Glencore 2023; Umicore 2024). Additionally, as described by Rosenbaum (2018), the impact category of CO_2eq is regarded as fairly certain, while others, such as human toxicity, are not (see section 3.2). Paper VI focuses on the conflicting goals that emerge from pyrometallurgical WEEE recycling. On the one hand, the recycling raises CE, while on the other hand, it reduces decarbonization due to the incineration of the plastic fraction of the WEEE.

The alternative decarbonization strategies identified in Paper VI may be to some extent limited by the fact that they have not been assessed regarding their associated technical and economic risks. CCS is recognized for its comparatively high costs and the potential for future risks associated with leakage (Rubin, Davison, and Herzog 2015; Wennersten, Sun, and Li 2015). The proposed alternative of bioplastic lies outside the scope of the smelters and probably shifts the problem of climate change to the "tank or plate debate" (Reynolds 2018). This analysis, however, lies beyond the scope of this climate change impact study and was therefore not further analyzed.

In Paper VI it was found that transportation has only a marginal contribution to the overall impacts on climate change. A note of caution should be added to the underlying assumptions employed in the study. It was assumed that all WEEE produced in a given country is shipped from the respective capital to the closest smelter. This approach, however, is not without limitations. For instance, it fails to consider the potential existence of local WEEE hubs outside the capital cities, the possibility of choosing a smelter based on geopolitical or economic factors rather than proximity, and the shipment of different WEEE fractions to distinct plants. Given the absence of primary data as well as the constraints of time and resources, this simplified method was chosen, and its results should be considered as a first estimate.

7. Conclusion and future work

The present cumulative thesis encompasses and analyzes the representation of the material gold in common LCA databases and studies. The most significant production routes for gold, including industrial gold mines, industrial copper mines, ASM, high-value scrap, and WEEE, were examined in six peer-reviewed publications. A schematic representation of the gold mining and recycling routes, along with their representation in the aforementioned papers, is provided in Figure 21.

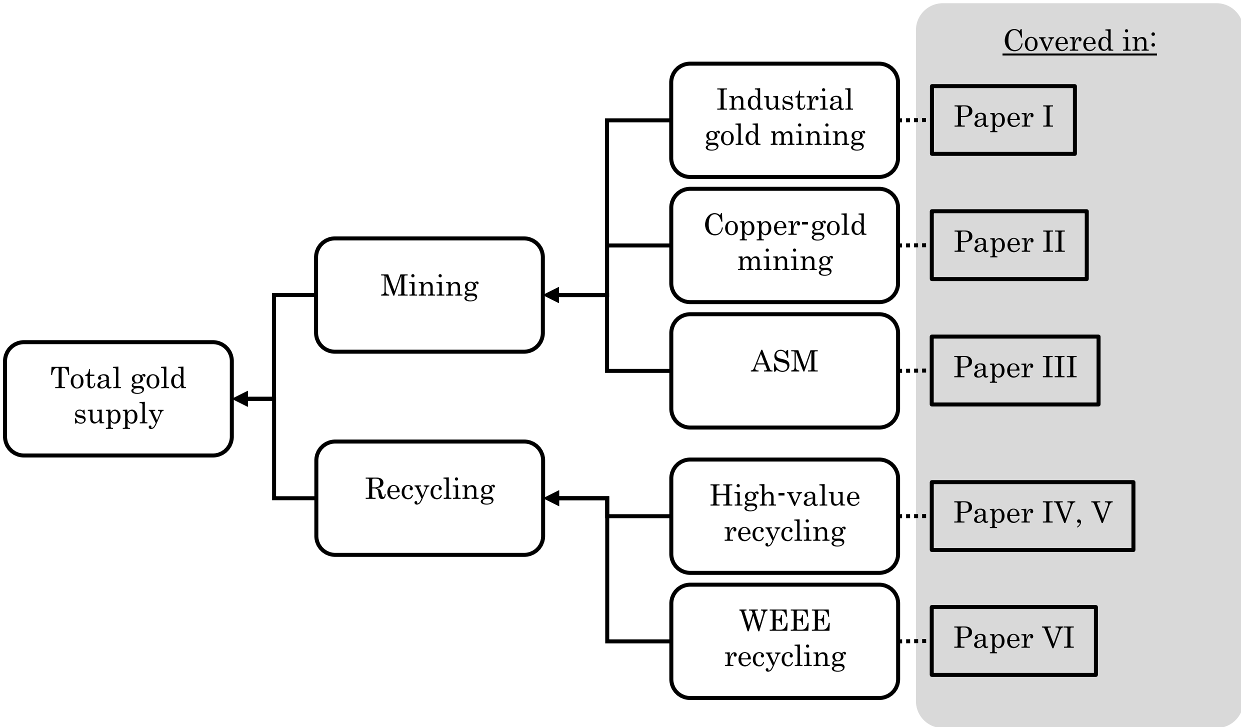


Figure 21: The "big picture": Overview of the main gold production routes in relation to each paper's contribution within this dissertation.

A comprehensive literature review (Paper I) revealed that existing LCA datasets for gold contain several vague assumptions for industrial gold mining and do not include gold production from high-value recycling and ASM (combined ≈30 % of the annual gold supply). This discrepancy leads to a misinterpretation of the environmental impacts associated with the global gold production (see Figure 16) in LCA databases (market datasets).

Paper II demonstrates that the allocation methods employed in LCA of gold, including the ones in accordance with ISO 14044, are used inconsistently and have substantial effects on the LCA results for gold (International Organization for Standardization 2020b). The ambiguity and possible inaccuracies in these methods introduce significant uncertainties to LCAs on gold (see Figure 17), particularly given the prevalence of base metal mines with gold as a by-product, such as copper mines, which constitute ≈10 % of gold mine production (Schütte et al. 2023).

In Paper III of the present dissertation, primary data on energy consumption as well as mercury use, loss, and recovery from over 100 data samples from 47 different ASM sites in the Brazilian Amazon rainforest were collected. A route not included in any LCA database so far. The findings indicate that the carbon footprint associated with gold production from ASM is lower but still within the magnitude of a typical industrial gold mine. Furthermore, approximately 2.5 tons of mercury are emitted to the environment by ASM in Brazil per year, even when employing retorts for the recycling of mercury (see Figure 18).

With regard to the second-highest gold-supplying route, high-value recycling, not included in common LCA datasets, the results show significantly lower environmental impacts compared to all other gold production routes (Figure 19) when no newly mined material is accepted as feedstock (Paper IV). A subsequent investigation in Paper V found that the implementation of additional technical and hydrometallurgical improvements to the process has the potential to result in a further reduction in the environmental impacts, e.g., reduce the carbon footprint by around 50 %.

Paper VI conducted a more in-depth investigation into the process of recycling gold from WEEE using pyrometallurgical methods, with the plastic fraction in the feedstock serving as both an energy carrier and a reduction agent. The combustion of the carbon content embedded in the plastics leads to a complex situation, as conventional industry strategies for decarbonization, such as the utilization of different energy carriers or reduction agents, prove to be inherently ineffective (Figure 20).

Despite the fact that a number of different environmental impacts were discussed in the various papers, the issue of climate change was the most prevalent theme. In a paper synthesis in section 5.7, it has been estimated that the carbon footprint of gold from the market mix is approximately 28 t CO_2eq/kg Au and that the total annual impacts on climate change are ≈110 Mt of CO_2eq. The latter is in a similar order of magnitude as the impacts on climate change of base metals, such as copper.

As was noted on multiple occasions throughout the course of the present thesis, the issue of transparency within the gold supply chain was a recurring theme. Consequently, the development of methods to enhance the reliability of the chain of custody and to promote greater transparency in the gold market, e.g., via blockchain, would be a fruitful area for further research.

The holistic approach of LCA offers the potential to address a broader range of environmental impacts beyond climate change. To fully leverage this potential, future studies would benefit from more comprehensive primary data on industrial mining practices, e.g., measured emissions to water and soil from tailings or detailed land use data before and after mining operations. This would enable a more comprehensive assessment of additional impact categories like land degradation or ecotoxicity, which are highly relevant in the context of gold production.

A stronger focus on the topic of regionalized LCA for the material gold could produce interesting findings. Especially the results of this thesis on ASM (Paper III) with data from Brazil and high-value recycling (Papers IV and V) with data from Germany could benefit from results for more regions. In contrast to this, parts of the criticism made in the discussion of IDS (Paper I) are related to focusing too much on regionalization. In current LCA databases for gold mining, datasets are primarily grouped by region rather than by geological and technological differences. Future studies should investigate whether alternative clustering approaches—beyond regionalization—could improve data quality and representativeness.

Future studies should assess some of the recommendations discussed based on first and rough assessments, e.g., scenario analysis (Paper V) or transport modeling (Paper VI) in more detail. A natural progression of the possible improvements discussed in this thesis, such as alternative energy sources, CCS, or the use of bioplastics in WEEE, would be detailed feasibility studies including technical and economic aspects.

Gold's distinct characteristics, which set it apart from other mined materials such as coal and lithium, are crucial in understanding its role and value in the global economy. Unlike coal or lithium, which are mined for specific material properties and could be substituted by alternative energy carriers or battery metals, gold's unique properties are more complex. Gold's main demand is used for fashion, decoration, and investment and is greatly based on qualitative factors such as financial security, dreams, prestige, and status. One saying that I heard repeatedly during the course of this dissertation was *"digging for gold is like digging for money"*. This underscores the imperative to acknowledge the long-standing and likely enduring value of gold to humanity. Consequently, it is essential to make further efforts to reduce the environmental impacts associated with gold production.

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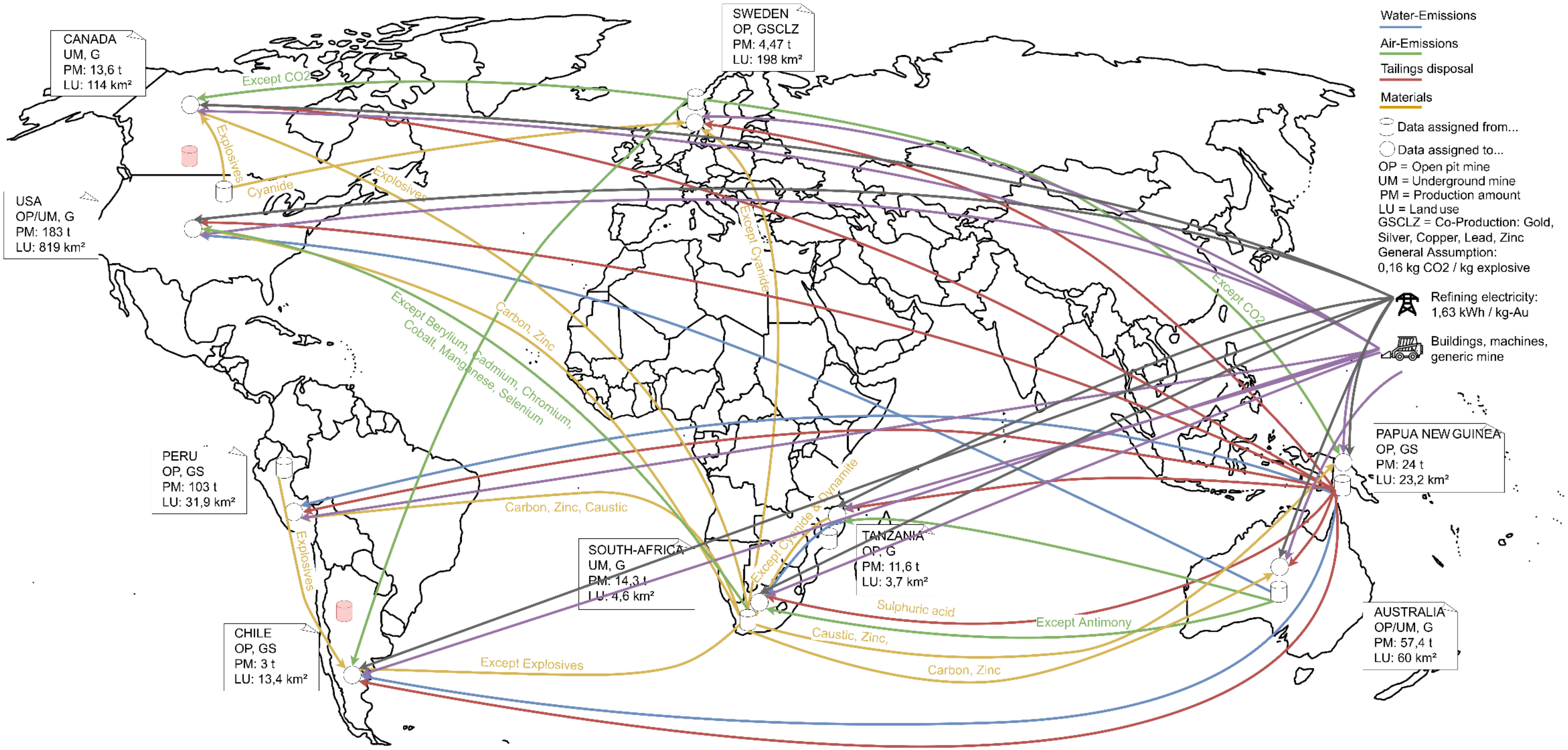
For the text of this dissertation, the AI-tools ChatGPT 3.0 by OpenAI (https://chatgpt.com) and DeepL (https://www.deepl.com) were used in selected sections exclusively for improving language, grammar and style and did not contribute to the generation of original content.

Appendix

A.1 Paper I – World map



Essential product flows in the ecoinvent database for gold mine production.
Own figure based on Classen et al. (2009) "LCI of Metals".

Figure A 1: High-quality graphic of Fig. 8.5 from Paper I.

A.2 Paper II – Supplement

Supplement i: Organizational LCA

	TOTAL	Zn	Cu	Ni	Pb	Au	Ag	Te	Co	Pd	Pt	H_2SO_4
Mines												
Production Volume	340000000	200000000	89000000	10000000	46000000	5800	320000	36000	513000	760	930	
Scope 1 emissions	220000000											
Scope 2 emissions	81000000											
TOTAL CO_2eq	300000000											
Smelters												
Production Volume	2400000000	460000000	230000000	34000000	46000000[a]	20000	430000			760[b]		1600000000
Scope 1 emissions	410000000											
Scope 2 emissions	130000000											
TOTAL CO_2eq	550000000											
Prices (Boliden 2024:52)												
Price [$ US/ kg]		2.8	7.8	20	2.0	45000	650	35	440	42000	29000	0.072[c]
Allocation mines												
Revenue	2300000000	550000000	690000000	200000000	92000000	260000000	210000000	1200000	230000000	32000000	27000000	
TOTAL CO_2eq (MA[d])	300000000	170000000	78000000	8700000	40000000	5000	280000	31000	450000	660	810	
TOTAL CO_2eq (EA[d])	300000000	71000000	90000000	26000000	12000000	34000000	27000000	160000	29000000	4200000	3500000	
SPECIFIC CO_2eq (MA)		0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	
SPECIFIC CO_2eq (EA)		0.36	1.0	2.6	0.26	5900	84	4.6	57	5400	3800	
Allocation smelters												
Revenue	5200000000	1300000000	1800000000	680000000	92000000	910000000	270000000			32000000		120000000
TOTAL CO_2eq (MA)	550000000	110000000	51000000	7700000	11000000	4600	97000			170		370000000
TOTAL CO_2eq (EA)	550000000	140000000	190000000	72000000	9800000	97000000	29000000			3400000		12000000
SPECIFIC CO_2eq (MA)		0.23	0.23	0.23	0.23	0.23	0.23			0.23		0.23
SPECIFIC CO_2eq (EA)		0.30	0.83	2.1	0.21	4800	68			4500		0.01
Final corporate carbon footprint results by products												
TOTAL CO_2eq (MA)	470000000	270000000	130000000	16000000	51000000	9600	380000			840		
TOTAL CO_2eq (EA)	800000000	210000000	280000000	98000000	22000000	130000000	56000000			7500000		
SPECIFIC CO_2eq (MA)		1.1	1.1	1.1	1.1	1.1	1.1			1.1		
SPECIFIC CO_2eq (EA)		0.66	1.84	4.7	0.47	11000	150			9900		

a) The simplified assumption has been made that the sum of Pb in alloys and refined Pb is equal to the amount of Pb in the mining concentrate.
b) The simplified assumption has been made that the sum of Pd in the smelter concentrate is equal to the amount of Pd in the mining concentrate.
c) The arithmetic mean of prices for 2024 (Q4) of the regions North America, Asia-Pacific (APAC), Europe, and the Middle East and Africa (MEA) (ChemAnalyst 2024)
d) MA = mass allocation, EA = economic allocation

Table A 1: Production figures and CO_2eq as reported in Boliden (2024:130ff) to demonstrate product allocation based on a O-LCA. The values are rounded to two significant digits.

Supplement ii: Profit with or without precious metals for Kevitsa

	2016	2017	2018	2019	2020	2021	2022
Production figures							
Milled ore [kt]	4500	7900	7600	7500	9200	9500	10000
Cu [kg]	14000000	30000000	27000000	20000000	27000000	29000000	25000000
Ni [kg]	7400000	14000000	14000000	9000000	11000000	13000000	12000000
Co [kg]	320000	590000	590000	450000	500000	590000	620000
Au [kg]	330	650	630	410	580	640	540
Pd [kg]	560	1000	1200	700	860	1000	960
Pt [kg]	750	1400	1600	950	1300	1400	1200
Prices [US$ / kg] (The World Bank 2024)							
Cu	4,9	6,2	6,5	6	6,2	9,3	8,8
Ni	10	10	13	14	14	18	26
Co[a]	44	44	44	44	44	44	44
Au	40000	40000	41000	45000	57000	58000	58000
Pd[a]	42000	42000	42000	42000	42000	42000	42000
Pt	32000	30000	28000	28000	28000	35000	31000
Product revenues [US$]							
Cu revenue	69000000	180000000	180000000	120000000	170000000	270000000	220000000
Ni revenue	71000000	140000000	180000000	130000000	150000000	240000000	300000000
Co revenue	14000000	26000000	26000000	20000000	22000000	26000000	28000000
Au revenue	13000000	26000000	26000000	18000000	33000000	37000000	31000000
Pd revenue	23000000	43000000	48000000	29000000	36000000	43000000	40000000
Pt revenue	24000000	43000000	45000000	26000000	36000000	51000000	38000000
TOTAL revenue	220000000	470000000	510000000	340000000	450000000	660000000	660000000
Exchange rates used for calculating the SEK[b] values from Boliden (2024:133) to US$							
Exchange rate [US$/SEK]	0.12	0.12	0.12	0.11	0.11	0.12	0.10
Theoretical profit without precious metals [US$]							
Operating profit	19000000	100000000	110000000	7100000	35000000	210000000	230000000
Operating cost	200000000	360000000	400000000	330000000	410000000	450000000	440000000
Revenue w/o Au, Pd, Pt	150000000	350000000	390000000	260000000	340000000	530000000	550000000
Operating profit w/o Au, Pd, Pt[c]	-41000000	-7300000	-6400000	-67000000	-70000000	80000000	120000000

a) Based on Boliden (2024:52), conversion kg / oz T = 0.0311
b) SEK = Swedish krona
c) Ceteris paribus case, where the process technology and the associated costs are not influenced by the production of precious metals

Table A 2: Comparison of profit with or without the production of precious metals for the Kevitsa mine (Boliden 2024:130ff). The values are rounded to two significant digits.

Supplement iii: Application of economic allocation in the SKARN database

	Gold[a]			Copper[b]		
Allocation method	Arithmetic mean [kg CO_2eq/kg Au]	Amount of data points (n)	Standard deviation	Arithmetic mean [kg CO_2eq / kg Au]	Amount of data points (n)	Standard deviation
Process-specific (Au-DB[c])	28000	155	23000	3.0	155	2.5
Process-specific (Cu-DB)	39000	155	26000	5.1	155	2.7
Mass allocation	8.4	155	21	8.4	155	21
Economic allocation	39000	155	26000	4.2	155	2.8

a) Based on SKARN database Q4 2022 v1.0 for gold (reference year: 2020)
b) Based on SKARN database Q4 2022 v1.0 for copper (reference year: 2020)
c) DB = database

Table A 3: Applying different allocation methods to the Cu-Au-mines in the SKARN database. The values are rounded to two significant digits.

A.3 Paper III – Supplementary information

ST_I_Mercury

Measurement ID	Original measurements										Per kilogram of gold[a]				
	Date	Type of mining	sponge gold [g]	Hg lost [g]	Hg squeezed [g]	Hg recovered retort [g]	Hg recovered total, [g]	Hg used [g]	Retort efficiency [%]		Hg lost	Hg squeezed	Hg retort	Hg recovered unknown	Hg used
Hg03	03.03.2021	Baixão	650.4	77.8	316.5	577.4	577.4	655.2	58		0.137	0.5559	0.4583	na	1.151
Hg08	19.03.2021	Baixão	459.7	39.9	161.3	492.9	492.9	532.8	88		0.099	0.4009	0.8241	na	1.324
Hg10	26.03.2021	Baixão	294.5	115.6	102.9	218.9	218.9	334.4	38		0.4484	0.3992	0.4500	na	1.297
Hg11	30.03.2021	Baixão	261.0	14.9	141.0	264.1	264.1	279.0	81		0.065	0.6172	0.5388	na	1.221
Hg21	30.01.2022	Baixão	239.7	65.9	118.9	236.0	236	301.9	91		0.314	0.5667	0.5583	na	1.439
Hg22	06.02.2021	Baixão	138.8	69.6	138.1	240.1	240.1	309.8	88		0.573	1.1366	0.8398	na	2.550
Hg23	04.04.2021	Baixão	43.0	na	na	na	na	na	na		na	na	na	na	na
Hg26	25.02.2021	Baixão	565.8	31.2	163.6	459.4	459.4	490.6	73		0.063	0.3303	0.5973	na	0.9906
Hg28	23.12.2020	Baixão	105.1	16	132.8	210.7	210.7	226.6	90		0.174	1.4435	0.846	na	2.463
Hg29	31.12.2020	Baixão	100.4	50.3	152.4	222.4	222.4	272.7	85		0.573	1.7335	0.797	na	3.103
Hg31	07.01.2021	Baixão	170.0	33.8	91.3	212.6	212.6	246.4	92		0.227	0.614	0.8185	na	1.655
Hg32	17.01.2021	Baixão	106.6	24	64.7	146.9	146.9	170.8	84		0.257	0.693	0.881	na	1.831
Hg33	24.01.2021	Baixão	106.9	49.2	93.0	153.5	153.5	202.8	61		0.526	0.99	0.647	na	2.167
Hg34	27.01.2021	Baixão	8.5	10.3	60.0	66.1	66.1	76.3	77		1.4	8.1	0.81	na	10
Hg35	30.01.2021	Baixão	239.7	65.9	118.9	236.0	236	301.9	91		0.314	0.5666	0.5583	na	1.439
Hg36	06.02.2021	Baixão	133.8	69.6	138.1	240.1	240.1	309.8	85		0.595	1.179	0.8712	na	2.645
Hg37	23.01.2021	Baixão	197.7	36.6	157.0	269.9	269.9	306.5	96		0.212	0.9072	0.6526	na	1.771
Hg38	24.01.2021	Baixão	264.2	26	34.8	320.2	320.2	346.3	95		0.212	0.1503	1.2340	na	1.497
Hg39	15.01.2021	Baixão	185.2	15.8	130.1	325.1	325.1	340.9	96		0.098	0.8025	1.2030	na	2.103
Hg40	16.01.2021	Baixão	379.3	275.7	196.2	225.8	225.8	501.4	10		0.8302	0.5909	0.089	na	1.510
Hg41	19.01.2021	Baixão	172.5	132.9	12.2	21.3	21.3	154.2	6.8		0.8802	0.081	0.06	na	1.021
Hg42	12.01.2021	Baixão	86.4	31.0	23.7	95.1	95.1	126.1	89		0.4098	0.313	0.945	na	1.67
Hg43	27.01.2021	Baixão	70.6	24.0	171.1	227.0	227	250.9	84		0.388	2.769	0.903	na	4.06
Hg44	27.09.2021	Baixão	354.0	94.6	194.6	427.1	427.1	521.8	91		0.305	0.6279	0.7505	na	1.684
Hg45	Jun/jul 2019	Baixão	322.1	15.9	na	230.7	230.7	246.6	na		0.056	na	na	0.82	0.8746
Hg46	Jun/jul 2019	Baixão	248.9	4.1	na	142.3	142.3	146.4	na		0.019	na	na	0.65	0.6720
Hg47	Jun/jul 2019	Baixão	273.3	14.1	na	154.1	154.1	168.2	na		0.059	na	na	0.64	0.7031
Hg56	07.10.2020	Baixão	118.0	na	na	na	na	na	95		na	na	1.1970	na	na
Hg57	17.10.2020	Baixão	40.1	na	na	28.7	28.7	32.3	90		na	na	0.735	0.82	0.920
Hg58	18.10.2020	Baixão	384.2	na	na	115.3	115.3	318.4	36		na	na	0.3417	0.34	0.9468
Hg09	20.03.2021	Draga	501.8	12.2	190.1	536.0	536.0	548.3	92		0.028	0.4328	0.7875	na	1.248

Table A 4: In situ measurement points for mercury use, recovery and loss in different ASM site.

Hg13	14.04.2021	Draga	114.7	-0.6	146.7	60.0	206.7	206.1	86	0	1.461	0.598	na	2.053
Hg14	16.04.2021	Draga	280.9	80.8	167.1	96.7	263.8	344.6	52	0.329	0.6798	0.393	na	1.402
Hg15	18.04.2021	Draga	221.0	19.0	129.8	118.2	248.0	267.0	79	0.0984	0.6709	0.6110	na	1.380
Hg16	20.04.2021	Draga	245.6	17.3	188.6	138.3	326.9	344.2	83	0.08042	0.8773	0.6433	na	1.601
Hg17	22.04.2021	Draga	157.4	7.9	109.8	89.7	199.5	207.4	85	0.057	0.7970	0.651	na	1.505
Hg18	24.04.2021	Draga	199.5	6.6	133.0	111.5	244.5	251.1	88	0.038	0.7617	0.6385	na	1.438
Hg19	26.04.2021	Draga	493.3	75.9	337.1	261.4	598.3	674.7	74	0.1760	0.7808	0.6054	na	1.563
Hg20	28.04.2021	Draga	209.8	12.6	180.6	120.3	300.9	313.6	87	0.0687	0.9836	0.6551	na	1.707
Hg24	20.02.2021	Draga	368.1	-6.10	115.4	251.4	366.8	360.7	91	-0.019	0.3581	0.7802	na	1.120
Hg25	24.02.2021	Draga	402.4	-58.1	108.9	280.1	389.0	330.9	92	-0.165	0.3092	0.7952	na	0.9395
Hg27	06.08.2022	Draga	155.5	15.6	24.3	125.5	149.8	165.4	91	0.115	0.179	0.9220	na	1.215
Hg30	06.01.2021	Draga	207.8	8.5	150.3	116.2	266.5	275.0	91	0.0469	0.8263	0.6387	na	1.512
Hg48	Jun/jul 2019	Draga	116.4	7.6	na	na	70.0	77.6	na	0.0746	na	na	0.69	0.762
Hg49	Jun/jul 2019	Draga	142.1	6.5	na	na	114.5	121.0	na	0.052	na	na	0.92	0.973
Hg50	Jun/jul 2019	Draga	na	na	na	na	na	na	na	na	na	na	na	na
Hg51	Jun/jul 2019	Draga	na	na	na	na	na	na	na	na	na	na	na	na
Hg53	03.10.2020	Draga	193.1	na	na	111.3	na	151.1	79	na	na	0.6585	na	0.8939
Hg54	04.10.2020	Draga	171.1	13.8	na	na	85.4	125.1	na	0.0921	na	na	0.57	0.8355
Hg55	05.10.2020	Draga	151.4	-279.6	337.1	123.8	na	181.3	96	-2.110	2.544	0.9341	na	1.368
Hg01	08.01.2021	na	228.4	na	na	na	na	na	na	na	na	na	na	na
Hg02	10.01.2021	na	205.0	na	na	na	na	na	na	na	na	na	na	na
Hg04	08.03.2021	na	353.0	na	na	na	na	na	na	na	na	na	na	na
Hg05	10.03.2021	na	225.3	na	na	na	na	na	na	na	na	na	na	na
Hg06	12.03.2021	na	347.6	na	na	na	na	na	na	na	na	na	na	na
Hg07	14.03.2021	na	306.9	na	na	na	na	na	na	na	na	na	na	na
Hg12	12.04.2021	na	188.8	na	na	na	na	na	na	na	na	na	na	na
Gold content of sponge gold is estimated to be 0.8753 (see supplementary Table A 17)														

Table A 5 (continued)

Arithmetic mean	Weight [kg/kg Au]	number	SD
Mercury used	1.7	46	1.4
Mercury lost	0.19	43	0.46

Table A 6: Arithmetic means of the mercury measurements.

ID internal	Mercury [BRL[a]/kg]
HG$01	1050
HG$02	1400
HG$03	1500
HG$04	1600
HG$05	1200
HG$06	1500
Arithmetic mean	1400
a) BRL = Brazilian real	

Table A 7: Cost of mercury.

ST_II_Retort application

Interviewee	Date	Profession	Age	Type	Retort	Question	Relation
RET01	02.08.2022	Socio	19	Draga	yes	Burning duration	indirect
RET02	04.08.2022	Manager	29	Filão	yes	Step-by-step process, burning duration	none
RET03	04.08.2022	Socio	63	na	yes	Description how to separate	none
RET04	05.08.2022	Dono	na	na	yes	Description how to separate	none
RET05	06.08.2022	Socio	31	Draga	yes	worked without retort before?	indirect
RET06	06.08.2022	Socio	na	Draga	contradiction	open conversation	indirect
RET07	06.08.2022	Manager	na	Draga	yes	open conversation	direct
RET08	07.08.2022	Socio	29	Baixão	no	worked without retort before?	indirect
RET09	07.08.2022	Manager	45	Baixão	yes	worked without retort before? burning duration	indirect
RET10	08.08.2022	Socio	34	Draga	yes	worked without retort before?	indirect
RET11	08.08.2022	Socio	66	Draga	yes	open conversation	indirect
RET12	10.08.2022	Manager	na	Baixão	no	observation	direct
RET13	10.08.2022	Socio	56	na	yes	Step-by-step process	none
RET14	11.08.2022	Manager	55	Baixão	yes	open conversation	direct
RET15	11.08.2022	Socio	58	Baixão	no	worked without retort before?	indirect
RET16	11.08.2022	Socio	28	Baixão	yes	worked without retort before?	indirect
RET17	11.08.2022	Socio	43	Baixão	yes	worked without retort before?	indirect
RET18	12.08.2022	Manager	na	Draga	yes	open conversation	direct
RET19	13.08.2022	Dono	46	Baixão, Filão	yes	open conversation	direct
RET20	12.08.2022	Dono	57	Baixão	yes	open conversation	direct
RET21	13.08.2022	Socio	na	na	yes	How did you burn this gold (gold is visible in the gold shop)	none
RET22	13.08.2022	Socio	na	na	yes	How did you burn this gold (gold is visible in the gold shop)	none
RET23	13.08.2022	Socio	na	na	yes	How did you burn this gold (gold is visible in the gold shop)	none
RET24	13.08.2022	Socio	na	na	yes	How did you burn this gold (gold is visible in the gold shop)	none

Table A 8: Interview results on the subject of retort application in the study area.

RET25	13.08.2022	Socio	na	na	yes	How did you burn this gold (gold is visible in the gold shop)	none
RET26	13.08.2022	Socio	na	na	yes	How did you burn this gold (gold is visible in the gold shop)	none
RET27	13.08.2022	Dono	69	Baixão	no	open conversation	direct
RET28	13.08.2022	Socio	23	Baixão	yes	step-by-step process	indirect
RET29	14.08.2022	Socio	29	Baixão	yes	open conversation	none
RET30	14.08.2022	Socio	62	Baixão	yes	historical development	indirect
RET31	14.08.2022	Socio	60	na	yes	historical development	indirect
RET32	14.08.2022	Socio	70	na	yes	historical development	indirect
RET33	14.08.2022	Socio	46	Filão	no	step-by-step process	indirect
RET34	16.08.2022	Dona	55	Baixão	contradiction	open conversation	direct
RET35	15.08.2022	Manager	50	Baixão	yes	step-by-step process	none
RET36	15.08.2022	Socio	60	Baixão	yes	Description how to separate	none
RET37	15.08.2022	Manager	31	Baixão	yes	open conversation	direct
RET38	15.08.2022	Socio	60	Baixão	yes	How did you burn this gold (gold is visible in the gold shop)	none
RET39	15.08.2022	Socio	50	Baixão	yes	step-by-step process	none
RET40	16.08.2022	Socio	39	Filão	yes	step-by-step process	none
RET41	16.08.2022	Dono	53	Baixão	yes	step-by-step process	none
RET42	18.08.2022	Dono	na	Draga	yes	open conversation	none
Total							
Yes	35	88 %					
No	5	13 %					
Manager	8						
Garimpeiro	27						
Dono	7						

Table A 9 (continued)

ST_III_Energy

Measurement ID	Type of mining	Doré/ Au [g/pit]	Doré/ Au [g/week]	Doré/ Au [g/year]	Doré/ Au [g/month]	Doré/ Au [g/day]	Reference product
E01	Baixão	360	na	Na	na	na	Au
E02	Baixão	520	na	Na	na	na	Doré
E03	Baixão	260	na	Na	na	na	Au
E04	Baixão	360	na	Na	na	na	Au
E05	Baixão	390	na	Na	na	na	Au
E06	Baixão	1400	na	Na	na	na	Au
E07	Baixão	650	na	Na	na	na	Doré
E08	Baixão	230	na	Na	na	na	Dorè
E09	Baixão	200	na	Na	na	na	Dorè
E13	Baixão	250	na	Na	na	na	Dorè
E14	Baixão	450	na	Na	na	na	Dorè
E15	Baixão	350	na	Na	na	na	Dorè
E16	Baixão	17000	na	Na	na	na	Dorè
E17	Baixão	1100	na	Na	na	na	Dorè
E18	Baixão	280	na	Na	na	na	Dorè
E19	Baixão	na	na	20000	na	na	Dorè
E20	Baixão	na	na	22000	na	na	Dorè
E21	Baixão	na	na	25000	na	na	Dorè
E22	Baixão	200	na	na	na	na	Dorè
E23	Baixão	230	na	na	na	na	Dorè
E25	Baixão	na	na	na	150	na	Dorè
E26	Baixão	300	na	na	Na	na	Dorè
E27	Baixão	95	na	na	Na	na	Dorè
E28	Draga	na	na	na	na	90	Dorè
E29	Draga	na	na	na	na	110	Dorè
E30	Draga	na	na	na	na	140	Dorè
E31	Draga	na	na	na	na	60	Dorè
E32	Draga	na	na	na	na	120	Dorè
E33	Filão	40000	na	na	na	Na	Dorè
E34	Filão	48000	na	na	na	Na	Dorè
E24	no excavator	na	na	na	190	Na	Dorè
E10	no excavator	na	45	na	na	Na	Dorè
E11	no excavator	na	45	na	na	Na	Dorè
E12	no excavator	na	45	na	na	Na	Dorè
Serabi	Serabi	na	na	na	na	1200000	Au

Table A 10: Energy demand in ASM based on interviews. The values are rounded to two significant digits.

Measurement ID	Excavator, Diesel [L/ pit]	Grinding, milling [L/shaft]	Pump, Diesel [L/pit]	Pump, Diesel [L/week]	Generator, Diesel [L/pit]	Petrol [L/pit]	Total diesel [L/day]	Total electricity [L diesel-eq./year]	Total Fuel [L/pit]	Total Fuel [L/week]	Total Fuel [L/year]	Total Fuel [L/month]
E01	900	na	960	na	110	25	na	na	2400	na	na	na
E02	1100	na	780	na	200	20	na	na	2100	na	na	na
E03	600	na	1100	na	38	90	na	na	1900	na	na	na
E04	720	na	1300	na	100	24	na	na	2200	na	na	na
E05	900	na	720	na	170	25	na	na	1800	na	na	na
E06	3900	na	2200	na	170	66	na	na	6300	na	na	na
E07	1200	na	480	na	26	100	na	na	2200	na	na	na
E08	560	na	400	na	120	na	na	na	1100	na	na	na
E09	300	na	400	na	60	150	na	na	910	na	na	na
E13	500	na	750	na	150	10	na	na	1400	na	na	na
E14	1100	na	1100	na	300	20	na	na	2500	na	na	na
E15	690	na	1100	na	200	14	na	na	2000	na	na	na
E16	3800	na	360	na	420	28	na	na	4600	na	na	na
E17	2300	na	420	na	270	18	na	na	30000	na	na	na
E18	520	na	900	na	200	160	na	na	1800	na	na	na
E19	na	na	na	na	na	na	na	na	na	na	110000	na
E20	na	na	na	na	na	na	na	na	na	na	100000	na
E21	na	na	na	na	na	na	na	na	na	na	120000	na
E22	480	na	630	na	60	60	na	na	1400	na	na	na
E23	500	na	420	na	na	na	na	na	1100	na	na	na
E25	na	na	na	na	na	na	na	na	na	na	na	1000
E26	1100	na	610	na	25	10	na	na	1700	na	na	na
E27	na	na	na	na	na	na	na	na	310	na	na	na
E28	na	na	na	na	na	na	550	na	na	na	na	na
E29	na	na	na	na	na	na	800	na	na	na	na	na
E30	na	na	na	na	na	na	1000	na	na	na	na	na
E31	na	na	na	na	na	na	400	na	na	na	na	na
E32	na	na	na	na	na	na	1000	na	na	na	na	na
E33	6800	5400	na	na	60000	1200	na	na	na	na	na	na
E34	4500	5800	na	na	100000	1600	na	na	na	na	na	na
E24	na	na	na	na	na	na	na	na	na	na	na	1000
E10	na	na	na	400	na	na	na	na	na	400	na	na
E11	na	na	na	400	na	na	na	na	na	400	na	na
E12	na	na	na	400	na	na	na	na	na	400	na	na
Serabi	na	na	na	na	na	na	3300000	2000000	na	na	na	na

Table A 11 (continued)

ID	Fuel data converted to kilogram and per kilogram of gold[a]							Total		
	Diesel[b], total [kg]	Diesel, excavator [kg]	Diesel, pump [kg]	Diesel, grinding & milling [kg]	Diesel, generator [kg]	Petrol[c,d], diesel-eq [kg]	Electricity, diesel-eq [kg]	Fuel	Diesel	Petrol
E01	na	2100	2200	na	260	49	na	4600	4600	52
E02	na	2000	1400	na	360	31	na	3700	3700	32
E03	na	1900	3400	na	120	240	na	5700	5400	250
E04	na	1700	3000	na	240	47	na	4900	4700	50
E05	na	1900	1500	na	370	46	na	3900	3800	48
E06	na	2200	1200	na	95	33	na	3600	3600	34
E07	na	1800	680	na	37	120	na	2600	2500	130
E08	na	2200	1600	na	470	na	na	4300	4300	na
E09	na	1400	1800	na	280	590	na	4100	3500	620
E13	na	1800	2800	na	550	31	na	5200	5200	33
E14	na	2300	2100	na	610	35	na	5100	5100	37
E15	na	1800	3000	na	530	30	na	5300	5300	32
E16	na	2100	200	na	230	13	na	2500	2500	14
E17	na	1900	350	na	220	13	na	2400	2400	13
E18	na	1700	3000	na	660	450	na	5900	5400	470
E19	4970	na	na	na	na	na	na	5000	5000	na
E20	4230	na	na	na	na	na	na	4200	4200	na
E21	4480	na	na	na	na	na	na	4500	4500	na
E22	na	2200	2900	na	280	240	na	5600	5400	250
E23	na	2000	1700	na	na	na	na	3800	3800	na
E25	6130	na	na	na	na	na	na	6100	6100	na
E26	na	3400	1900	na	77	26	na	5300	5300	28
E27	3020	na	na	na	na	na	na	3000	3000	na
E28	5470	na	na	na	na	na	na	5500	5500	na
E29	6520	na	na	na	na	na	na	6500	6500	na
E30	6640	na	na	na	na	na	na	6600	6600	na
E31	5970	na	na	na	na	na	na	6000	6000	na
E32	7460	na	na	na	na	na	na	7500	7500	na
E33	na	180	na	140	1600	27	na	2000	1900	28
E34	na	100	na	130	2200	30	na	2500	2500	31
E24	4840	na	na	na	na	na	na	4800	4800	na
E10	na	na	8200	na	na	na	na	8200	8200	na
E11	na	na	8200	na	na	na	na	8200	8200	na

Table A 12 (continued)

E12	na	na	8200	na	na	na	na	8200	8200	0
Serabi	2400	na	na	na	na	na	1400	3800	2400	0

a) Gold content of sponge gold is estimated to be 0.8753 (see supplementary Table A 17)
b) Diesel density = 0.8325 kg/L (Deutsches Institut für Normung 2022)
c) Petrol density = 0.7475 kg/L (Deutsches Institut für Normung 2017)
d) Heating value diesel = 43 MJ/kg, heating value petrol = 40.95 MJ/kg (Hoinkis 2016)

Table A 10 (continued)

Arithmetic mean	Fuel [kg/kg Au]	Amount	SD
primary deposit, underground	2200	2	260
Secondary deposit, Overground, with excavator	4400	23	1100
Secondary deposits, dredge	6400	5	670
Secondary deposit, surface, without excavator	7300	4	1400

Table A 13: Arithmetic mean of the fuel consumption values based on Table A 10.

ST_IV_Climate impacts

Sector	Type of mining	Diesel [kg diesel]	Electricity [kWh]	Petrol [kg petrol]	Explosives [kg explosives]	Transport of diesel [kg diesel]	Source	[kg CO_2eq/kg Au]					
								Diesel	Electricity	Petrol	Explosives	Transport	Total
ASGM	Prim.[a] deposit, UG[b], ASGM	2200		30	20	330	(Fritz, Peregovich, et al. 2023)	8400		120	90	1300	
ASGM	Sec.[a] deposit, SF[b], w/[c] excavator	4400		91		330	(Fritz, Peregovich, et al. 2023)	16000		370		1300	
ASGM	Sec. deposit, dredge	6400				330	(Fritz, Peregovich, et al. 2023)	24000				1300	
ASGM	Sec. deposit, SF, w/o[c] excavator	7300				330	(Fritz, Peregovich, et al. 2023)	28000				1300	
LSGM	Prim. deposit, UG, LSGM	2400	6200				Serabi, LSGM, Brazil (company visit, 2018)	9100	980				
LSGM	LSGM mix						SKARN (2022), database for LSGM[d]						21000
Market	Gold market						ecoinvent v.3.9.1, gold market[e]						4800
Market	Gold market						(WGC 2019)						37000
Recycling	Recycling mix						(Fritz et al. 2020)						53

a) Prim. = primary; sec. = secondary
b) UG = underground; SF = surface
c) w/ = with; w/o = without
d) Based on SKARN database Q4 2022 v1.0 for gold
e) Ecoinvent v.3.9.1, market for gold

Table A 14: Estimation of the impacts on climate change from ASM. The values are rounded to two significant digits.

Process	Reference	Climate impact [kg CO_2/kg]	Climate impact [kg CO_2/kWh]
Market for diesel - BR[a] - diesel	ecoinvent 3.9.1	0.64	
Market for petrol, unleaded - BR - petrol, unleaded	ecoinvent 3.9.1	0.85	
Burning of diesel	(UBA 2016)	3.2	
Burning of petrol	(UBA 2016)	3.2	
Market electricity BR	ecoinvent 3.9.1		0.16
Diesel, burned in building machine - GLO[b]	ecoinvent 3.9.1	4.2	
Market for blasting - GLO - blasting	ecoinvent 3.9.1	5.0	
a) BR = Brazil b) GLO = Global			

Table A 15: Ecoinvent datasets used for calculating the impacts on climate change from ASM. The values are rounded to two significant digits.

ST_V_Au mass fraction

Interviewee ID	Region	Profession	Type of mining	Au content
AU%01	Creporizao	Gold shop	Baixão	0.91
AU%02	Creporizao	Gold shop	Draga	0.93
AU%03	Creporizao	Gold shop	Filão	0.89
AU%04	na	Geologist	Baixão	0.89
AU%05	na	Geologist	Filão	0.79
AU%06	na	Geologist	Ouro Mil	0.99
AU%07	Cuiu-Cuiu	Gold shop	Filão	0.77
AU%08	Cuiu-Cuiu	Gold shop	Baixão	0.90
AU%09	Creporizao	Gold shop	Draga	0.94
AU%10	Itaituba	Gold shop	Baixão	0.92
AU%11	Itaituba	Gold shop	Draga	0.94
AU%12	Itaituba	Gold shop	Filão	0.73
AU%13	Itaituba	Gold shop	Baixão	0.92
AU%14	Itaituba	Gold shop	Draga	0.93
AU%15	Itaituba	Gold shop	Filão	0.73
AU%16	Itaituba	Gold shop	Baixão	0.90
AU%17	Itaituba	Gold shop	Draga	0.92
AU%18	Itaituba	Gold shop	Filão	0.76
AU%19	Moraes Almeida	Gold shop	Baixão	0.90
AU%20	Moraes Almeida	Gold shop	Draga	0.94
AU%21	Moraes Almeida	Gold shop	Filão	0.78
AU%22	Moraes Almeida	Gold shop	Baixão	0.92
AU%23	Moraes Almeida	Gold shop	Draga	0.94
AU%24	Moraes Almeida	Gold shop	Filão	0.80
AU%25	Rio do Rato	Dono	Baixão	0.93
AU%26	Rio Marupa	Dono	Baixão	0.88
AU%27	Rio Marupa	Dono	Draga	0.90
Arithmetic mean of Au in doré for the different mining types				
Baixão	90.5 %			
Filão	77.8 %			
Draga	92.9 %			

Table A 16: Gold content in doré.

ID internal	Date	Type of mining	Sponge gold [g]	Doré [g]	Au [g]	Au content
SP%01	03.10.2020	Draga	193.1	179.0	166.4	86.15 %
SP%02	02.10.2020	Draga	151.4	138.8	129.0	85.20 %
SP%03	06.08.2022	Draga	179.6	170.1	158.1	88.02 %
SP%04	04.08.2022	Draga	545.5	522.6	485.7	89.04 %
SP%05	04.08.2022	Draga	217.3	200.8	186.6	85.88 %
SP%06	02.08.2022	Draga	292.9	283.2	263.2	89.86 %
SP%07	26.07.2022	Draga	192.6	181.2	168.4	87.44 %
SP%08	26.07.2022	Draga	415.3	384.0	356.9	85.93 %
SP%09	28.07.2022	Draga	na	na		
SP%10	30.07.2022	Draga	129.3	125.5	116.6	90.21 %
SP%11	31.07.2022	Draga	282.8	264.9	246.2	8.057 %
SP%12	01.08.2022	Draga	191.9	181.9	169.1	88.09 %
Arithmetic mean of Au wt% in sponge gold						87.53 %

Table A 17: Weight ratio between sponge gold and doré for twelve samples.

A.4 Paper IV – Electronic supplementary material

a. Transportation worst case scenario

One of the precious metal recycling facilities has provided us with their shipping quantities and weights broken down by the different qualities of scrap. On average, one kg of gold had a gross shipping weight of 2.55 kg in year 2018. We assume that all shipments to the smelter have to be transported on average 300 km. We then further assume that this transport is done with a light commercial vehicle and not a semi-trailer or train. The ecoinvent data set market for transport, freight, light commercial vehicle [Europe without Switzerland] gives 1.87 kg CO_2eq/ton*km. Multiplying the 0.0025 tons with 300 km and 1.87 kg CO_2eq/ton*km equals to 1.4 kg CO_2eq./kg Au. After allocation by mass to the gold content of the scrap shipments, this then makes 0.54 kg CO_2eq/kg Au or a share of 1 % of the total greenhouse potential (53 kg CO_2eq./kg Au). Even if allocated by monetary value, the result is still only 2.4 % of the total greenhouse potential.

b. Allocation

For the calculation of the allocation factors by mass the products (i) mass (M_i) has to be divided by the sum of all (n) the products masses. The calculation of the allocation factor by mass is then as follows $\frac{M_i}{\sum_{i=1}^{n} M_i}$.

The economic allocation factor for a given product (i) is calculated by multiplying the mass (M_i) of the product by its unit market price (P_i), and dividing by the total economic value of all by-products. The calculation of the allocation factor is then as follows $\frac{P_i * M_i}{\sum_{i=1}^{n} P_i * M_i}$.

Product	Price of metal in EUR
Gold	34136.16
Silver	496.37
Copper	5.09
Palladium	19939.14
Platinum	31224.51

Table A 18: Market prices (average prices from 2013 to 2018) for different commodities used for environmental impact allocation. EUR = Euro currency.

The allocation factors used in this study can be found in Table A 19.

Product (Mass)	Allocation factor by mass	Allocation factor by monetary value
Gold (1 kg)	64 %	92 %
Silver, in silver chloride (0.45 kg)	3.8 %	0.60 %
Palladium, in solution (59 g)	2.8 %	3.2 %
Platinum, in solution (44 g)	29 %	3.7 %

Table A 19: Allocation factors used in this study (rounded).

A more detailed analysis of the total impact results for the global warming potential (GWP) and cumulative energy demand (CED) for the different allocation methods is shown in Figure A 2.

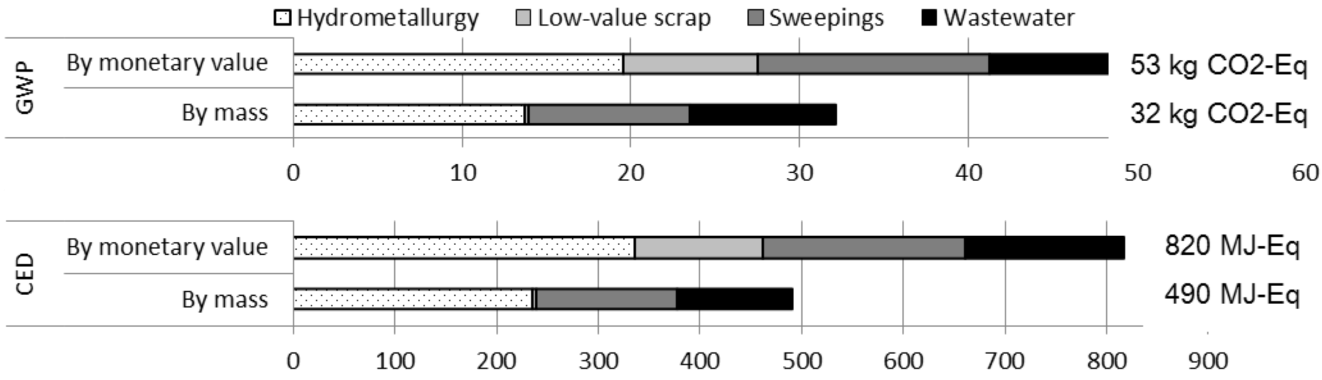


Figure A 2: Impact results for GWP and CED by process phase allocated by mass vs. monetary value.

c. Ecoinvent processes

Process name	**Geography**	**Purpose in this study**
market for electricity, medium voltage	Germany [DE]	Temperature regulation, stirring and wastewater treatment
activated carbon production, granular from hard coal	Europe [RER]	Cleaning of flue gasses
market for tap water	Switzerland [CH]	Cooling and solidifying gold granulates
nitric acid production, product in 50% solution state	Europe [RER]	Dissolving gold in aqua regia
market for hydrochloric acid, without water, in 30% solution state	Europe [RER]	Dissolving gold in aqua regia
hydrogen peroxide production, product in 50% solution state	Europe [RER]	Dissolving gold in aqua regia
market for sulfuric acid	Europe [RER]	Electrolysis in low-value scrap preparation
market for quicklime, milled, loose	Switzerland [CH]	Adjusting the pH value
natural gas production	Germany [DE]	Smelting, incineration and drying
market for sodium hydroxide, without water, in 50% solution state	Global [GLO]	Cleaning of wastewater
treatment of wastewater from wafer fabrication, capacity 1.1E10l/year	Switzerland [CH]	Cleaning of wastewater
market for sulfur dioxide, liquid	Europe [RER]	Precipitating gold in aqua regia

Table A 20: Ecoinvent v.3.5 processes and their geographical locations used to develop the cradle-to-gate inventory.

d. Literature review

Relevant Impact Categories	Acronym	Best characterization model	Unit	Espi (2009)	Kennecott (2016)	Thammaraksa (2017)	Pre (2012)	Nuss (2014)	Drielsma (2016)	Valdivia (2011)	Norgate (2012)	Mudd (2007)	TruCost (2017)	Li (2013)	Chen (2018)	Occurrence in %
Climate change	Global Warming Potential GWP	Baseline model of 100 years of the IPCC (Forster et al. 2007)	kg CO_2 eq	1	1	1		1		1	1	1	1	1	1	83%
Acidification Potential	Acidification Potential [AP]	Accumulated exceedance (Seppälä et al. 2006; Posch et al. 2008)	mol H+-Eq	1	1			1			1		1	1	1	58%
Resource depletion, water	[Water]	Model for water consumption as in the Swiss ecoscarcity (Frischknecht et al. 2008)	M3 water-Eq			1				1	1	1	1		1	50%
Energy demand	Cumulative Energy Demand [CED]	Cumulative energy demand	MJ-Eq	1	1		1	1				1				42%
Photochemical ozone formation	Photochemical ozone Creation Potential [POCP]	LOTOS-EUROS as applied in ReCiPe (Van Zelm et al. 2008)	Kg NMVOC-Eq		1	1					1			1	1	42%
Land use	[points]	Model based on soil organic matter (SOM) (Milà i Canals et al. 2007)	points	1						1		1	1		1	42%
Resource depletion, minerals and metals	Abiotic Depletion Potential [ADP	CML 2002 (Guinée et al. 2002)	kg Sb-Eq			1			1		1			1	1	42%
Ozone depletion	Ozone depletion Potential [ODP]	Steady-state ODPs from the WMO assessment (Montzka and Fraser 1999)	kg CFC-11-Eq			1					1			1	1	33%
Human toxicity, cancer effects	[HumToxCan]	USEtox model (Rosenbaum et al. 2008)	CTUh			1		1			1				1	33%
Human toxicity, non-cancer effects	[HumTox]	USEtox model (Rosenbaum et al. 2008)	CTUh			1		1			1				1	33%
Ecotoxicity, freshwater	[EcoTox fresh]	USEtox model, (Rosenbaum et al. 2008)	CTU			1					1		1		1	33%
Particulate matter/respiratory inorganics	Particulate Matter [PM]	Compilation in Humbert (2009) based on Rabl and Spadaro (2004) and Greco et al. (2007)	Disease incidence			1					1				1	25%
Eutrophication, aquatic / marine	Eutrophication Potential fresh-/marine water [EPfresh/ EPmar]	EUTREND model as implemented in ReCiPe (Struijs et al. 2009b)	kg P-Eq / kg N-Eq					1						1	1	25%

Espi JA, Morena SA (2010) The Scarcity-Abundance Relationship of Mineral Resource Introducing some Sustainability Aspects. DYNA 77:21–29; Kennecott Utah Copper (2007) Gold Environmental Profile - Life Cycle Assessment. http://www.kennecott.com/library/media/Gold%20Environmental%20Profile%202006.pdf. Accessed Nov 2017; Thammaraksa C, Wattanawan A, Prapaspongsa T (2017) Corporate environmental assessment of a large jewelry company. From a life cycle assessment to green industry. Journal of Cleaner Production 164:485–494. doi:10.1016/j.jclepro.2017.06.220; PRé (2012) LIfe cycle Assessment for a major jewelry manufacturer. https://www.pre-sustainability.com/download/Life-cycle-assessment-for-a-major-jewelry-manufacturer-A4.pdf. Accessed 06.2020; Nuss P, Eckelman MJ (2014) Life cycle assessment of metals: a scientific synthesis. PloS one 9(7):e101298. doi:10.1371/journal.pone.0101298; Drielsma JA, Russell-Vaccari AJ, Drnek T, Brady T, Weihed P, Mistry M, Simbor LP (2016) Mineral resources in life cycle impact assessment—defining the path forward. Int J Life Cycle Assess 21(1):85–105. doi:10.1007/s11367-015-0991-7; Valdivia SM, Ugaya CML (2011) Life Cycle Inventories of Gold Artisanal and Small-Scale Mining Activities in Peru. Journal of Industrial Ecology 15(6):922–936. doi:10.1111/j.1530-9290.2011.00379.x; Norgate T, Haque N (2012) Using life cycle assessment to evaluate some environmental impacts of gold production. Journal of Cleaner Production 29-30:53–63. doi:10.1016/j.jclepro.2012.01.042; Mudd GM (2007) Global trends in gold mining. Towards quantifying environmental and resource sustainability. Resources Policy 32(1-2):42–56. doi:10.1016/j.resourpol.2007.05.002; Pandora, Trucost (2017) Material Sourcing Natural Capital Assessment and Net benefit Analysis. TruCost Assessment. https://pandoragroup.com/-/media/files/policies-and-statements/material-analysis-trucost.pdf. Accessed 06.2020; Chao Li et al. (2013) Life Cycle Assessment of different gold extraction processes. In: Energy Technology 2014 - Carbon Dioxide Management and Other Technologies. Wiley, J, Hoboken; Chen W, Geng Y, Hong J, Dong H, Cui X, Sun M, Zhang Q (2018) Life cycle assessment of gold production in China. Journal of Cleaner Production 179:143–150. doi:10.1016/j.jclepro.2018.01.114

Table A 21: List of commonly used impact categories in LCA studies subject to gold that match with the list of best characterizations models by Hauschild et al. (2013).

In Figure A 3 it is apparent that the variation of the literature data in the studies of mining is quite high

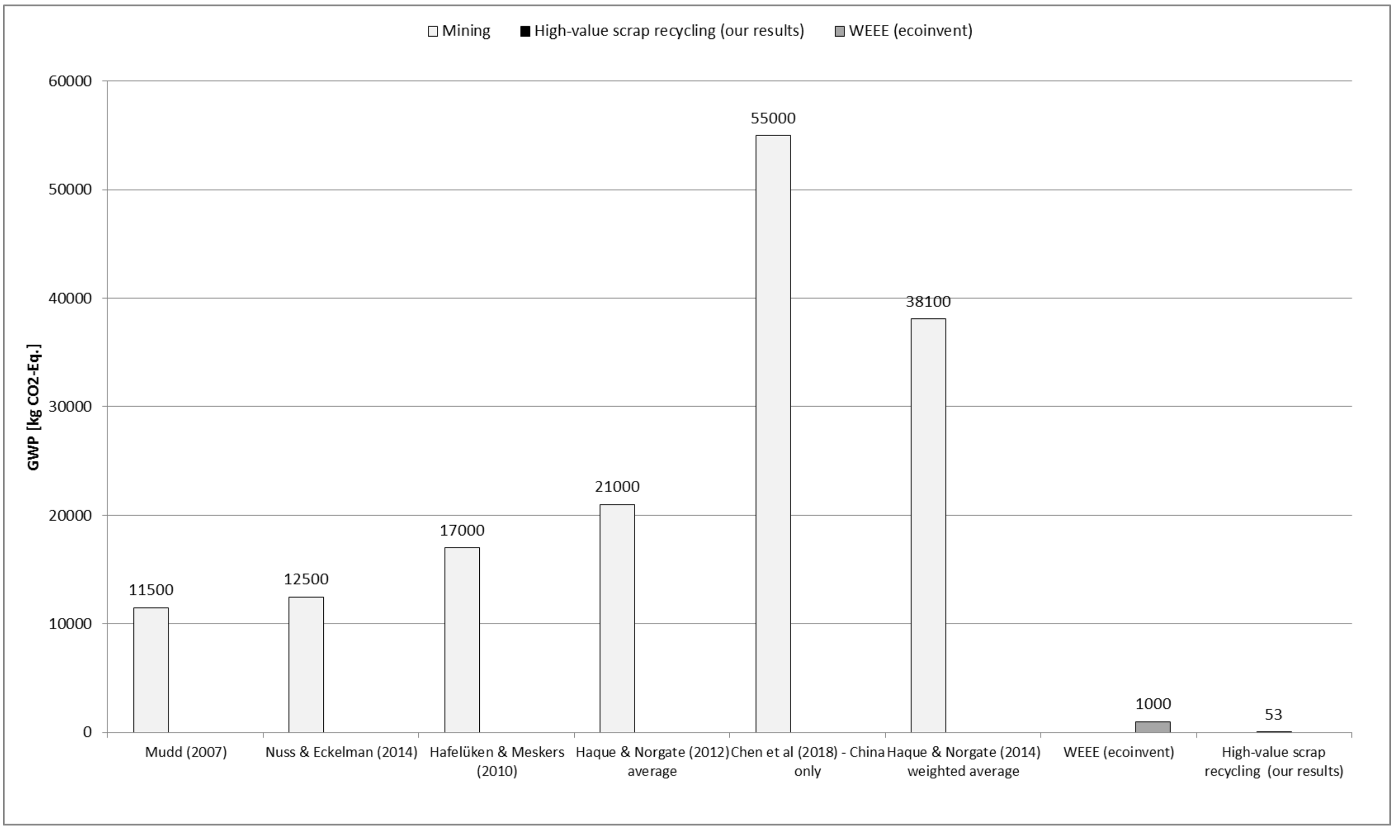


Figure A 3: Comparison of the global warming potential (GWP) for mining from other studies with the ecoinvent's data on WEEE recycling and this study's new data on the recycling of gold scraps. The figure is modified from the WGC (2018).

A.5 Paper VI - Supplementary materials

LCI Flow	Ecoinvent activity, v.3.10, cut-off	Region
Quicklime	Market for quicklime, milled, loose	RoW[a]
H_2SO_4	Market for sulfuric acid	Europe
Water	Market for water, completely softened	Europe
Oxygen	Market for oxygen, liquid	Europe
Electricity	Market for electricity, high voltage	Sweden
Natural gas	Market for heat, district or industrial, natural gas	Europe w/o CH[b]
Electricity (SC2)	Electricity production, hydro, run-of-river	Sweden
Smelter infrastructure	Copper smelting facility construction, SE	Sweden
Anode refinery infrastructure	Anode refinery construction	Sweden
Refinery infrastructure	Precious metal refinery construction	Sweden
Transport truck	Market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 4	RoW
Transport ship	Market for transport, freight, sea, container ship, heavy fuel oil	GLO[c]
Transport plane	Market for transport, freight, aircraft, unspecified	GLO
a) RoW = rest of world b) w/o CH = without Switzerland c) GLO = Global		

Table A 22: List of ecoinvent processes used in Paper VI.

Company	Region	Country	Capacity (Feliciano and González 2002)	Latitude	Longitude
Boliden	Rönnskär	Sweden	2.40×10^8	64°40'7.69"N	21°16'22.86"E
Umicore	Hoboken	Belgium	5.00×10^7	51° 9'58.56"N	4°20'1.02"E
Aurubis	Hamburg	Germany	4.20×10^8	53°30'49.37"N	10° 2'17.27"E
Aurubis	Lünen	Germany	1.70×10^8	51°36'19.10"N	7°30'26.92"E
Mitsubishi	Naoshima	Japan	2.70×10^8	34°28'20.68"N	133°58'35.95"E
Glencore	Horne	Canada	2.00×10^8	48°15'9.48"N	79° 1'2.94"W
LS-Nikko	Onsan	South Korea	4.50×10^8	35°26'8.15"N	129°20'51.20"E
DOWA	Kosaka	Japan	9.60×10^7	40°20'24.86"N	140°44'54.47"E
JX Nippon	Saganoseki	Japan	4.70×10^8	33°15'20.55"N	131°52'45.16"E
Montanwerke Brixlegg	Brixlegg	Austria	8.50×10^7	47°25'52.28"N	11°52'31.25"E

Table A 23: List of coordinates of smelters recycling gold from WEEE used for the transportation model.

Company	Closest airport	Distance to airport [km]
Boliden	Skelleftea	2.50×10^1
Umicore	Antwerp	1.50×10^1
Aurubis	Hamburg	3.00×10^1
Aurubis	Dortmund	3.00×10^1
Mitsubishi	Okayama	7.00×10^1
Glencore	Jack Garland	2.80×10^2
LS-Nikko	Daegu	1.30×10^2
DOWA	Akita	1.35×10^2
JX Nippon	Oita	9.50×10^1
Montanwerke Brixlegg	Innsbruck	5.50×10^1

Table A 24: List of closest airports to smelters recycling gold from WEEE including distances used for the transportation model.

Metal	Literature values [kg CO_2eq/kg metal]	Source	Metal content in WEEE according to Classen et al. (2009) [kg metal/kg Au]
Lead	2.68	ecoinvent v.3.11	9.43×10^1
Copper	8.24	ecoinvent v.3.11	1.40×10^3
Nickel	1.07×10^1	ecoinvent v.3.11	1.97×10^2
Silver	5.24×10^2	ecoinvent v.3.11	3.29×10^1
Gold	3.00×10^4	SKARN	1.00
Palladium	1.28×10^4	ecoinvent v.3.11	1.82

Table A 25: Literature values for comparing secondary with primary (mining) production.

Estimation of district heating potential for SC3

Entry	Symbol	Amount	Unit
Specific heat capacity	C_p	3.85×10^2	J/(kg*K)
Melting temperature	V_S	1.08×10^3	C
Temperature difference	ΔT	1.06×10^3	K
Amount of copper	m	1.39×10^3	kg
Thermal energy	ΔQ	5.70×10^8	J

Table A 26: Energy to bring copper to melting point.

Entry	Symbol	Amount	Unit
Specific heat capacity	C_p	9.20×10^2	J/(kg*K)
Melting temperature	V_S	2.00×10^3	C
Temperature difference	ΔT	1.06×10^3	K
Ceramic quantity	m	1.82×10^3	kg
Thermal energy	ΔQ	1.78×10^9	J

Table A 27: Energy to bring silica to melting point of copper.

Entry	Symbol	Amount	Unit
Amount of copper	m	1.39×10^3	kg
Specific heat of fusion	C_{melt}	2.05×10^5	J*kg
Smelting energy	ΔQ	2.85×10^8	J

Table A 28: Energy to melt copper.

Entry	Amount	Unit	Comment
Calorific value of plastics	3.67×10^7	J/kg	(Huang et al. 2018)
Quantity of plastic	1.81×10^3	kg	(Classen et al. 2009)
Available energy from plastic	6.62×10^{10}	J	Multiplication of the two rows above
Energy required for melting	2.64×10^9	J	Sum of ΔQ from table S5 to S7
Available energy after melting	6.36×10^{10}	J	Subtraction of the two rows above
Efficiency	80 %	-	
Heat available for district heating	5.09×10^{10}	J	Multiplication of the two rows above
Per kg blister copper	2.36×10^7	J	(Classen et al. 2009)

Table A 29: Available net energy for district heating.