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

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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

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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

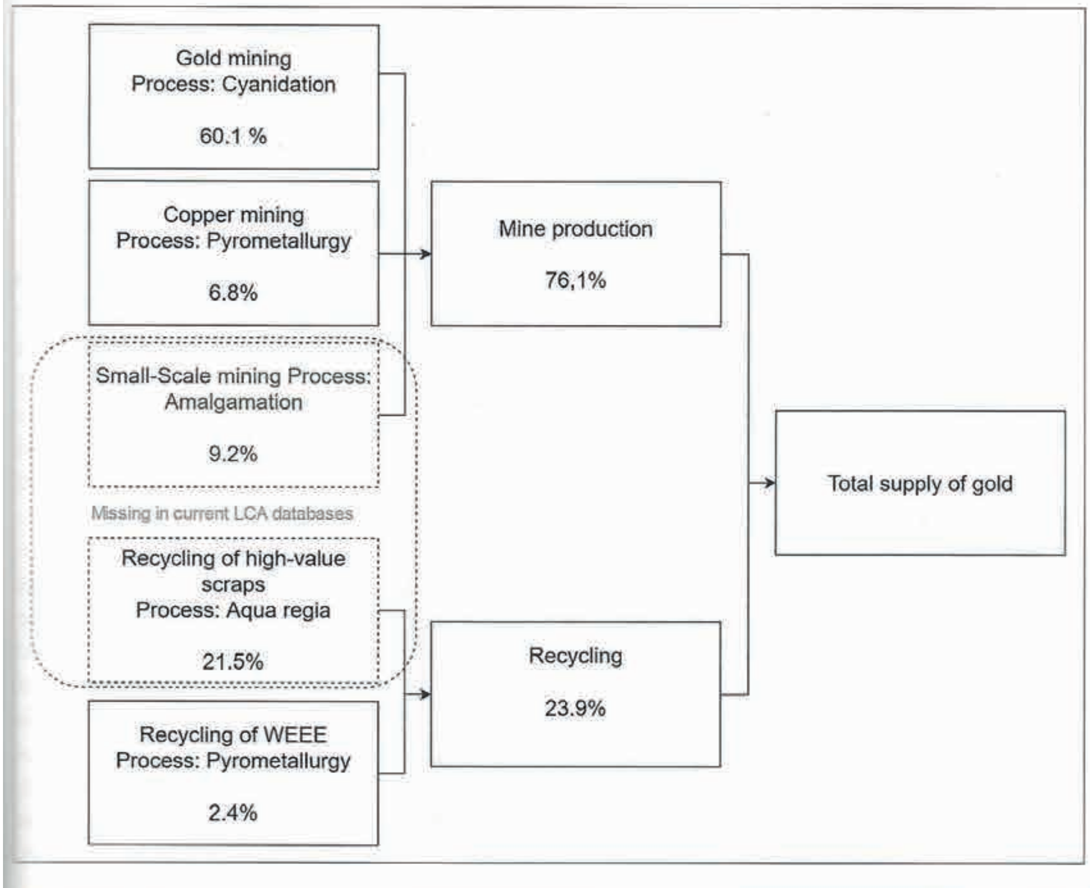

Fig. 1:
Comparison of global shares of different gold production processes; the dashed lined boxes are missing in common LCA databases (Figure adapted from Figure 8.2 in [17])

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 Inter-systemic-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.

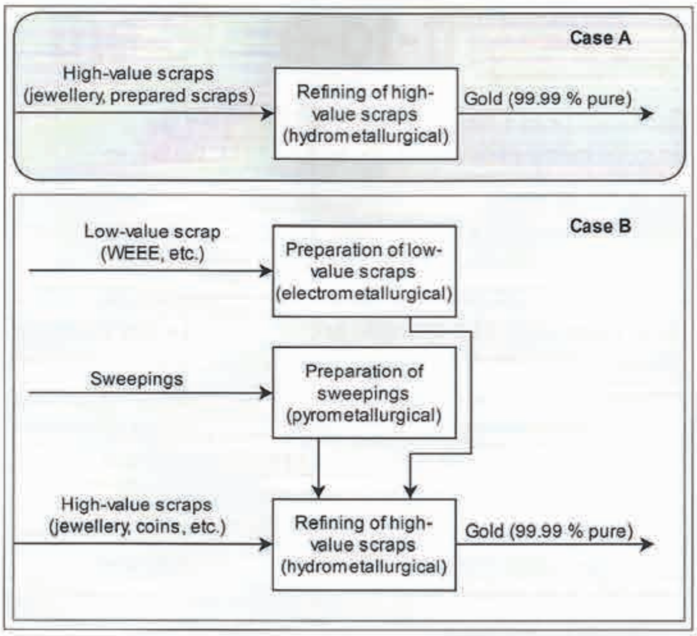

Fig. 2: The two different scenarios examined in this study

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

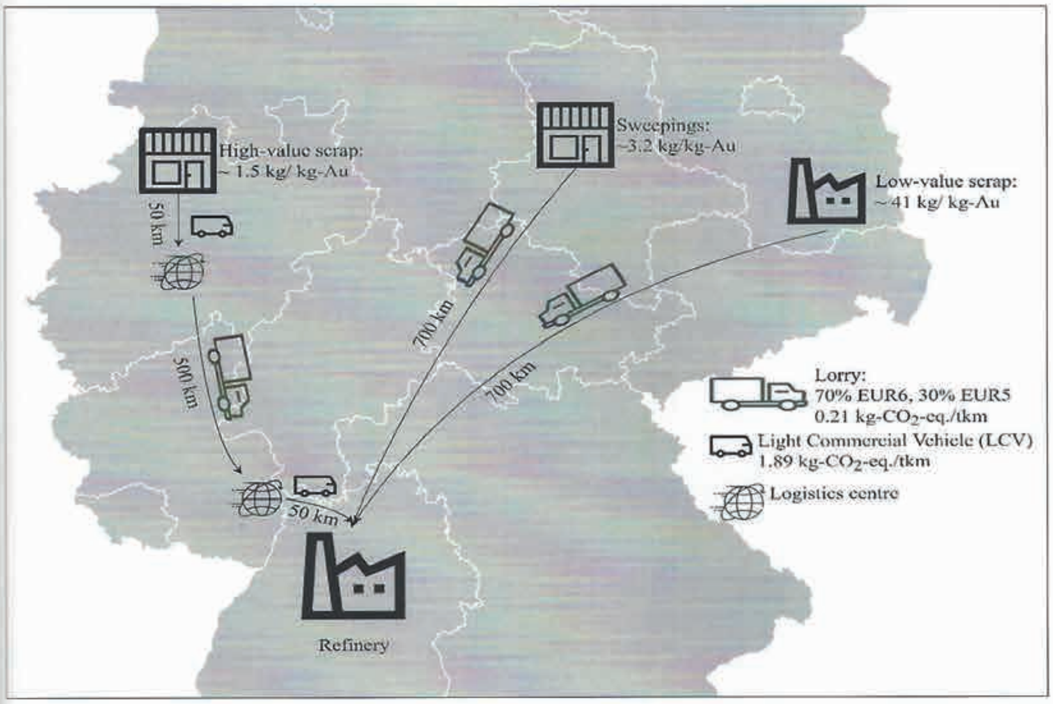

Fig. 3:
Modes of transport for the three scrap inputs in this study

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

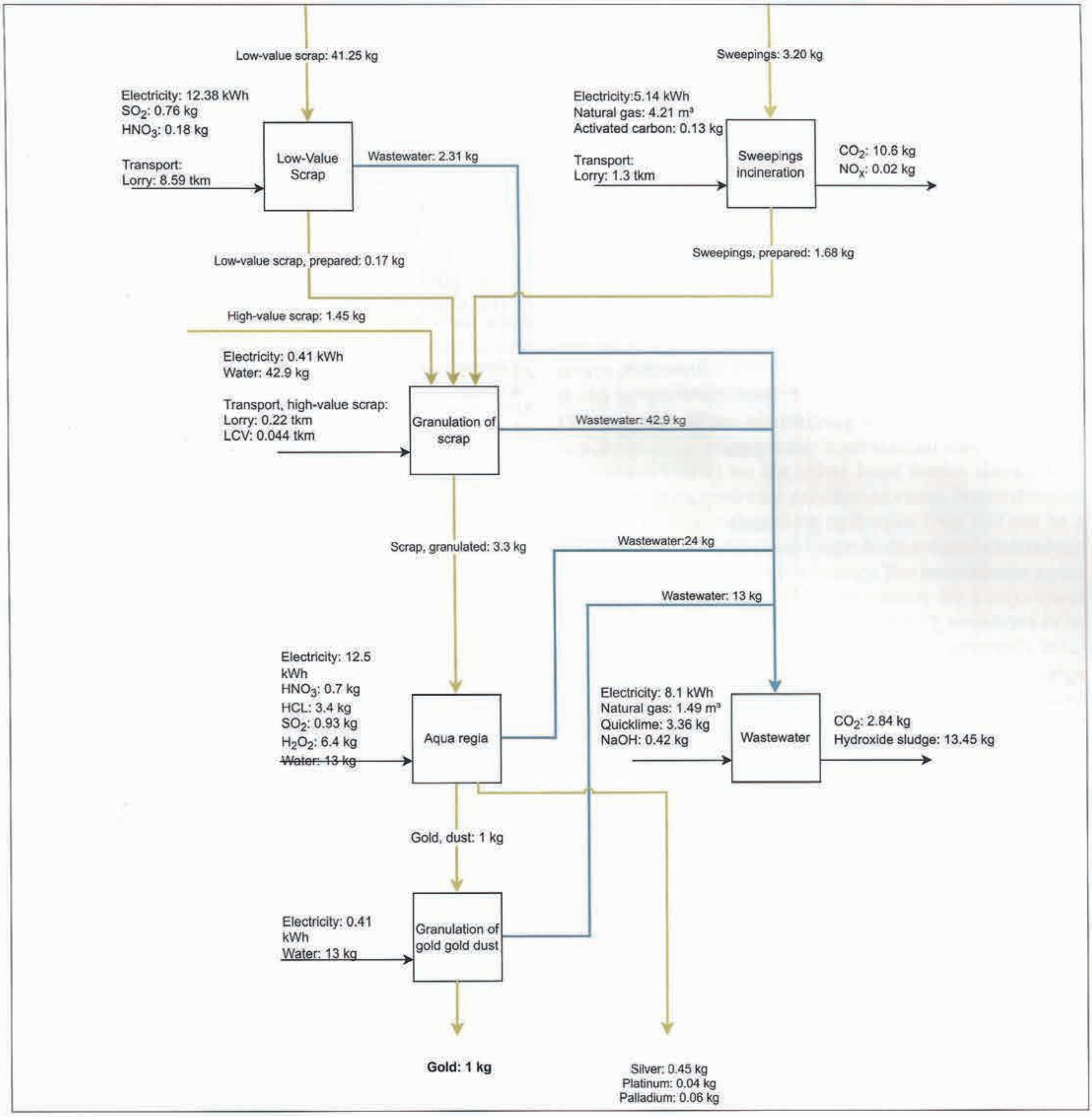

Fig. 4: Overview of the gold refining product system considered in this study

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

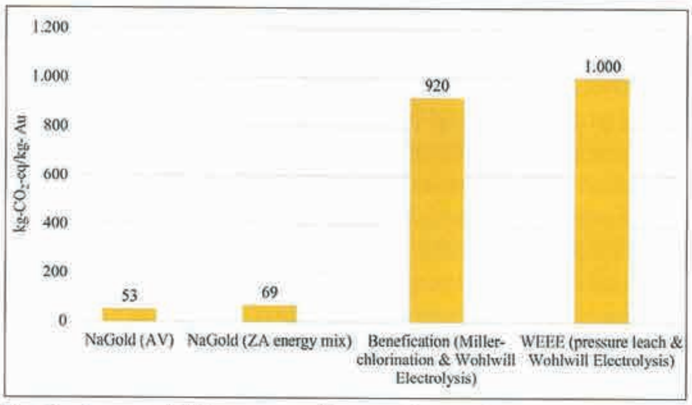

Fig. 7: Impact of different material types allocated by monetary values

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

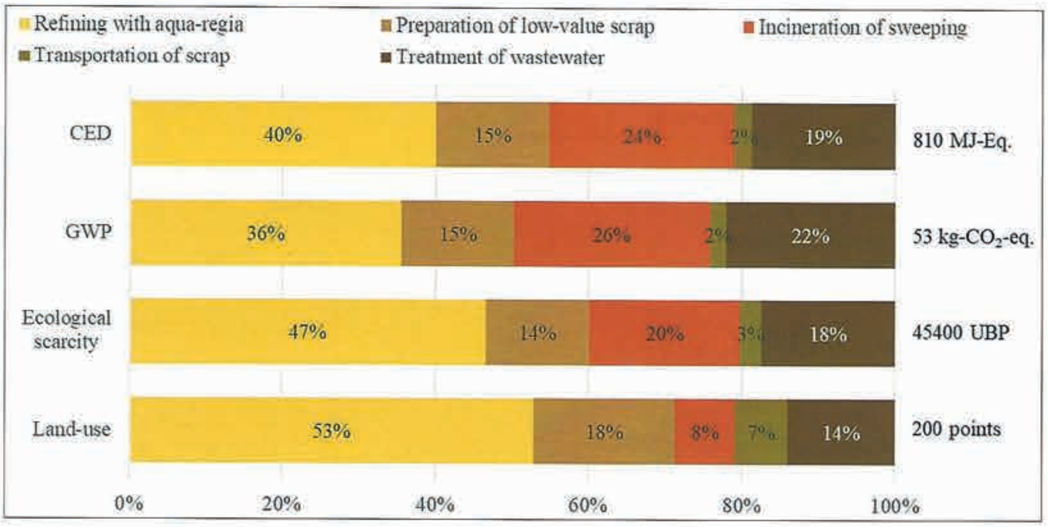

Fig. 5: Environmental impacts of high-value gold refining in Germany by processes

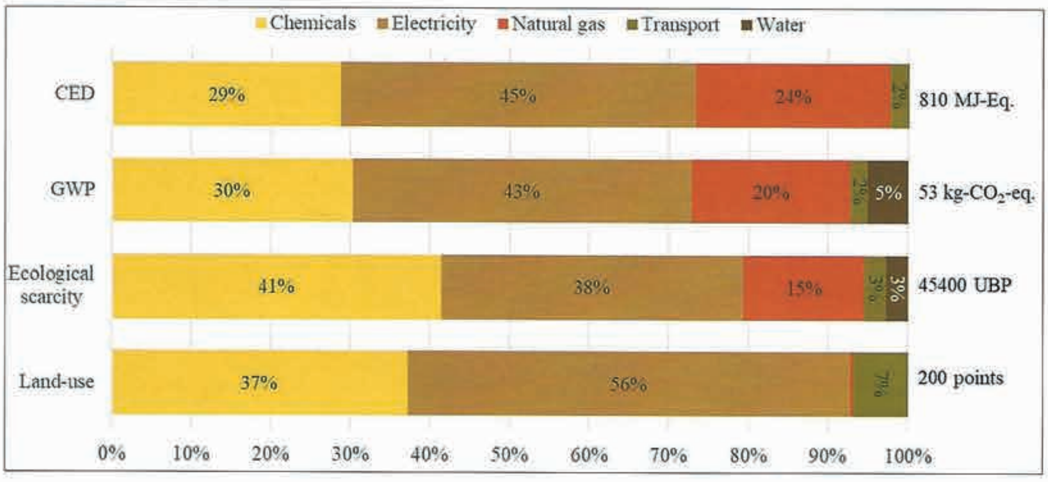

Fig. 6: Environmental impacts of gold refining in Germany by material types

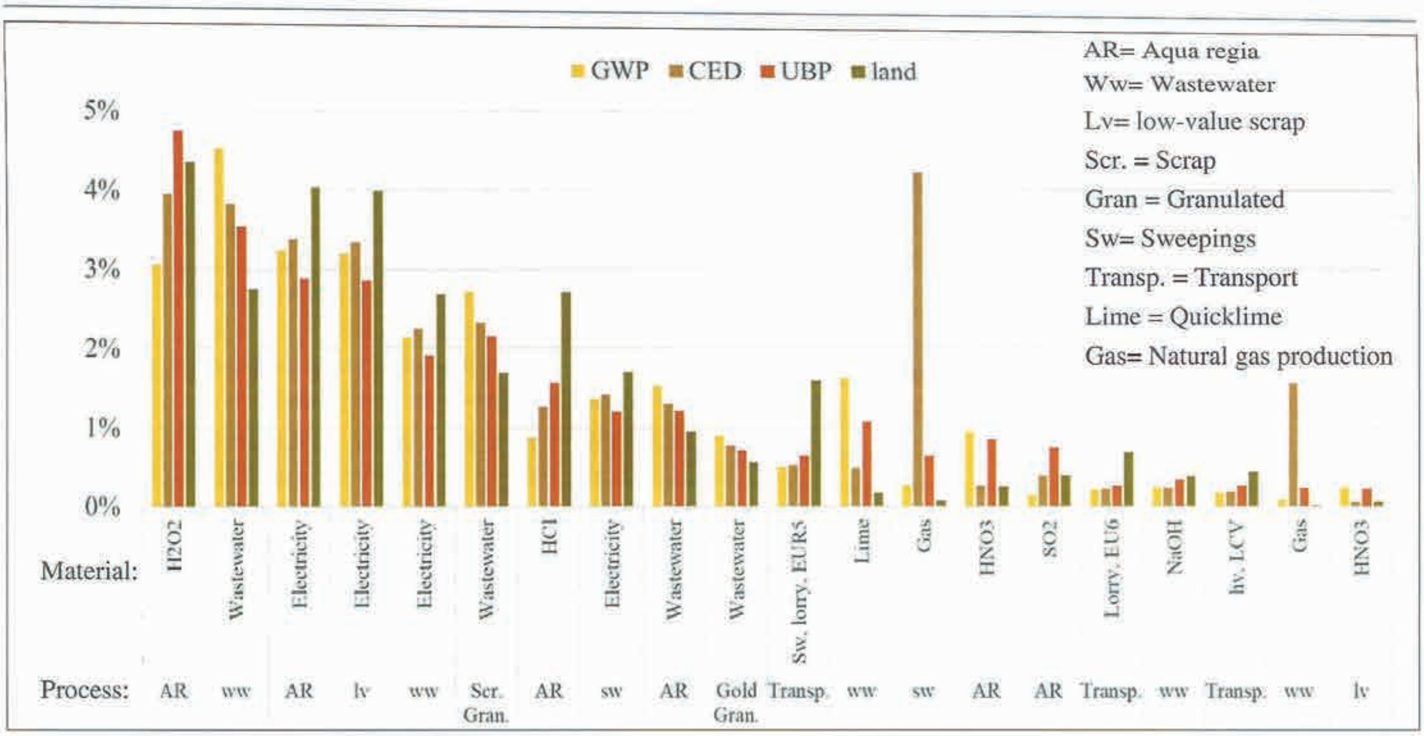

Fig. 8: The top 20 most sensitive processes (measured in percentage change to the overall result)

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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