1. The importance of gold

Gold (Au) has been valued as a precious material for thousands of years and today it used mainly as a form of investment: Financial investors are responsible for 30% to 40% of the demand, mostly in form of gold bars and coins as well as medals and exchange traded funds (ETFs) (Fig. 1).[38]

The production of jewellery (as a precious metal, gold maintains its luster and is soft, flexible and pliable) makes up about 40% of the demand. National banks require about 10% , industry as well.[21]

A common unit of measurement in the gold trade are troy ounces (oz tr) where a troy ounce in SI units corresponds to 31.1035 g.

Pure gold (24 carat) has a density of 19.32 g / m^3 and is obtained by mining from auriferous rock (gold ore or mountain gold) or won as free gold from sedimentary deposits (placer gold and alluvial gold).[20]

By 2011 an estimated total 171 300 t of gold[14,31] with a value of over CHF 4 800 billion (2004-2014: CHF 877 / oz tr)[13] were obtained from deposits.

It is estimated that there is more gold in circulation than can be currently mined from known reserves of geological deposits (54 000 t).[32]

Gold contents in mined ores have decreased from more than 50 g / t in 1850 to now under 2 g / t due to the increasing depletion of highly enriched deposits (Fig. 2).[18] This means that the mining waste generated during the production process has also been on the rise, although technological innovations in this area have contributed to increased efficiency (Fig. 2).

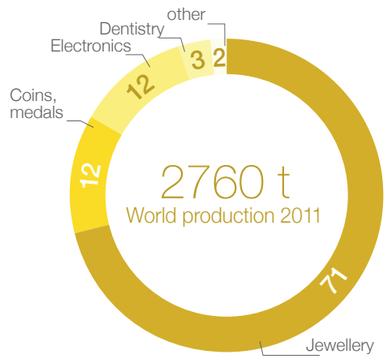


Fig. 1 World production and uses (as a percentage) of gold in 2012 (38).

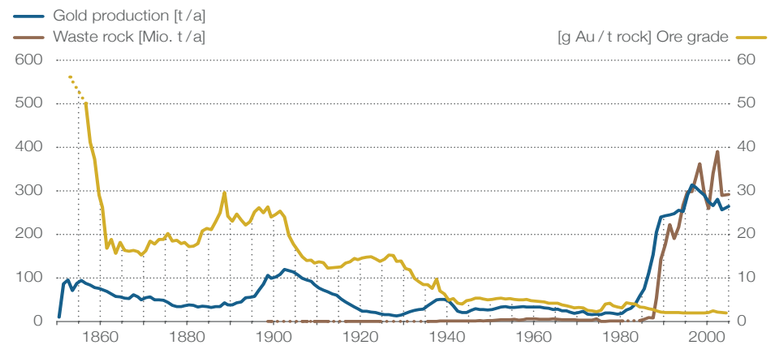


Fig. 2 Production, mining waste and ore content of gold, 1850-2005 (18).

2. Understanding the system

Although some of the naturally occurring gold deposits in Switzerland have technically exploitable concentrations of gold, for most the total content of recoverable gold is rather small and therefore the deposits are internationally insignificant.[15]

By contrast, Switzerland is the most important international gold hub; unlike the transit trade, in terms of quantity over two-thirds of the world's annual gold production physically passes through Switzerland. For example, according to the U.S. Geological Survey USGS, in 2012, 2 690 t of gold were extracted worldwide, the World Gold Council specifies it as being 2 827 t.[32,36] Whereas, in 2012, around 2 299 t were imported by Switzerland, mainly for refining, 1 631 t were exported.[7,8] Since 2014, Swiss foreign trade statistics show the flow of the gold trade broken down by country (Fig. 3)[6]; however, they do not specify the level of stock.[5]

The recycling of gold plays an important role in Switzerland, and, at an estimated 50%, the gold processed in Swiss refineries is most likely to contain a significant proportion of old gold.[9] Publicly available data on the material stocks and flows of gold is sorely lacking, particularly when it comes to the recoverable amounts of gold from waste in the technology sector (e.g. electrical and electronic equipment). The variable gold content in various products as well as the heterogeneous material composition of the collected and sorted waste represent a major challenge when collating data and creating models.

The potential recovery from waste is therefore difficult to quantify, and basic studies are needed for modelling the flows of gold.

Currently, Switzerland is a 'black box' with respect to the domestic material streams, and annual figures are only available from the declared customs and trade statistics.

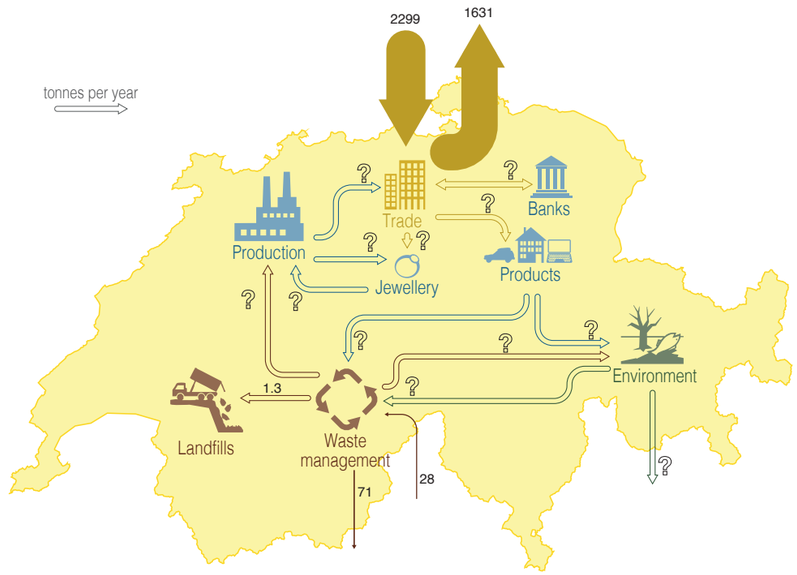


Fig. 3 Provisional material flow diagram (also lists the trading of auriferous waste) for Switzerland with data from customs statistics (7,8,17): The mass flows and stocks within Switzerland cannot currently be quantified.

7. Society

The global extraction of gold by independent miners and small-scale mining companies (artisanal gold mining) employs 10-20 million people and provides a livelihood for over 100 million people.[2,22] In 2012, the gold mining industry (excluding the artisanal gold mining) employed around 528 000 people with an average per capita value generation of 124 oz t (3.875 kg; approx. CHF 195 000).[35] In comparison, in 2012 the annual starting salary of a gold miner in South Africa was about CHF 5 900 [4] and the South African average was around CHF 14 500[33].

Serious long-term environmental damage and health risks of artisanal gold mining are often the result of the use of mercury. But also with respect to industrial gold mining, the damage and the consequences of accidents in many cases do not just affect the environment, but also the local population.[2, 9]

Compared to artisanal gold mining, the occupational safety and working conditions of miners in large mining companies are generally much better. Nevertheless, for example lung diseases caused by the inhalation of dust when mining quartz-rich rocks (silicosis) without sufficient health protection, are often associated with a risk in underground gold mining and lead to thousands of deaths every year. Internationally accepted minimum standards are widely implemented mainly to avoid damage to company reputation and strikes.

Complex company groups with local subsidiaries and non-transparent trade chains may unintentionally acquire gold from unregulated mining or even conflict regions. Thus a significant portion of the mined and traded gold is associated with serious consequences for the environment and the workers' health.

Switzerland is the most important gold hub in the world. The risk to reputations associated with gold mining due to possible human rights violations and environmental pollution is well-known in Switzerland. To counteract it, Switzerland actively engages in improving the working conditions of artisanal gold mining. This goal is pursued by the certification of trade chains, as well as by the development and implementation of international tools and standards to promote good corporate governance.[1, 5]

The certification of gold from fair and sustainable mining can generate added value through the issuing of labels, which in turn can be used for marketing.

This is the approach of the 'Better Gold Initiative'[25], which Switzerland launched in 2013. It should facilitate better working conditions for artisanal gold miner cooperatives and make 'Ethical gold' attractive to the consumer market, although the consumers would have to purchase the fair gold at a higher price.

By this, the Better Gold Initiative also contributes to the implementation of the 'OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas'.

In addition to the OECD Gold Supplement, there are different sets of rules (RJC Chain of Custody certification, LBMA Responsible Gold Guidance and Section 1502 of the Dodd Frank Act) that deal with the gold trade.[9] However, at the international level, there is for example currently no binding obligation for the observance of human rights in gold mining.[9]

8. Resource management: The overall situation at a glance

The high value of gold for example promotes jewellery being almost entirely recycled, since it can be easily collected through buyback mechanisms and requires a low level of refining.

By contrast, the rate of recovery of gold from waste is rather low. Gold is often only used in individual product components; the typically complex material composition and temporal variability of the amount of gold in the waste require greater recovery efforts and costs.

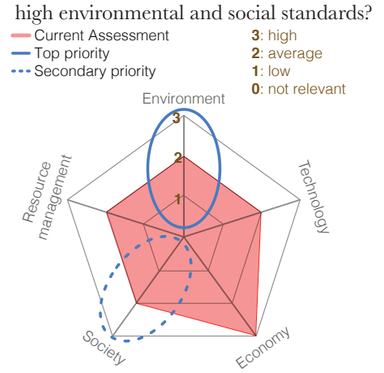
The current high price of gold, around CHF 37 000 / kg (January-March 2014)[13] is a special incentive at private-sector level, to recover gold from waste, provided that the waste contains a certain concentration and quantity of gold (Fig. 4).

In terms of environmental impact, energy consumption and greenhouse gas emissions, the primary production (mining) of gold has far worse impacts than the secondary production by recycling and recovery from dry MSWI slag and WEEE (Fig. 5).[34] This justifies the public investment in the development of recovery technologies for recycling gold from MSWI and electronic waste. The efforts of the Centre for Sustainable Waste and Resource Management ZAR have shown that gold from individual slag fractions (e.g. the non-ferrous metal fraction <5 mm) can be recovered profitably. The recycling of gold from electrical and electronic equipment can als be effectuated profitably in Switzerland.

Due to the legal regulations, the waste material is collected by private organisations. The development of better recycling technologies in this area could be financed from the prepaid disposal fees for electrical and electronic waste.

Open issues:

1. How high are the concentrations and mass flows of gold in electronic waste; how much of this is recyclable?
2. Is the collection and recycling technology for electrical and electronic equipment technically mature enough?
3. How can the dry slag discharge be promoted for other incineration facilites?
4. How can it be guaranteed that the recycling of exported electronic waste has high environmental and social standards?



▶ **Fig. 8** Evaluation of the Urban Mining Potential of gold (MSWI slag and waste electrical equipment) based on a qualitative expert assessment.
Criteria: *Environment*: Informal mining bad, mining companies better; *Technology*: Recovery from slag and electrical scrap; *Economy*:does not need measures, it runs by itself; *Society*: Informal mining bad, mining companies better; *Resource management*: Preparation of certificates for 'clean' gold, potential in slag still exists.

Literature
Due to limited space, the bibliographic references are summarised in a separate document.

http://daten.sgtk.ch/rohstoff-monitoring/AWEL_Gold_Literature_EN.pdf

This substance dossier was created by Mark Simoni and Benjamin Jost from the Swiss Geotechnical Commission SGTK in collaboration with the GEO Partner AG for the AWEL.

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3. Primary/secondary raw materials

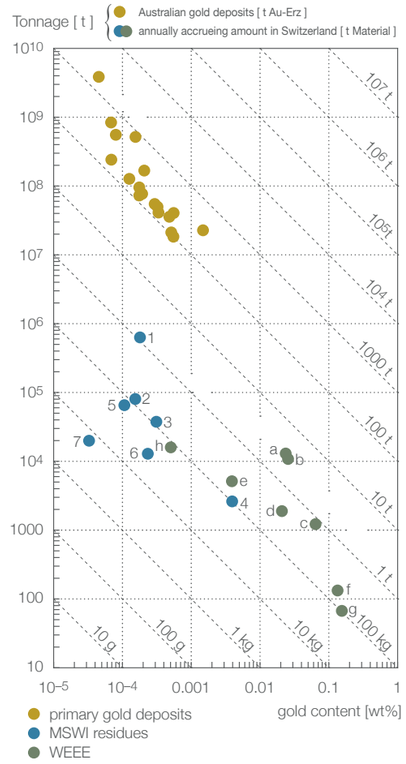
Gold is one of the rarer elements of the earth and naturally occurs in the form of 'primary' and 'secondary' gold deposits.

The term 'primary gold deposits', refers to mountain gold (ore mineralisation), where the gold has mostly accumulated in the rock in microscopic quantities through hydrothermal processes and must be extracted by hard rock mining and chemical processes. Typical gold ore minerals are sylvanite ($(Au, Ag)Te_4$) and calaverite ($AuTe_2$). In rare cases, native gold (free gold, Au (Ag, Cu, Hg, Pd)) is visible by the naked eye in veins and fissures.

Secondary placer or residual gold deposits are formed and concentrated through the weathering and / or erosion of auriferous rock on the surface. The current average level of recoverable gold ores in deposits of important mines lies at about 3 g / t.[21]

In Switzerland, for example, 53.4 kg of gold was excavated in Salanfe above Martigny between 1904-1929. The mined ore had a relatively high gold content of up to 35 g / t. .[23] In general, however, Swiss gold deposits are often small-scale (unfavourable geotectonic conditions) and additionally, larger-scale mining operations are not possible on account of regulatory and social reasons. The recovery of gold from urban stocks is especially interesting in electronics and electrical equipment (waste electric and electronic equipment, WEEE), since these can have an extremely high gold content (Fig. 4). For example, mobile phones were found to have a gold content of 982 g / t, and concentrations of 347 g / t were measured in the individual mobile phone circuit boards.[29] This equates to over a hundred times higher concentration of gold than is found in the currently mineable gold ore. Even municipal solid waste incinerator (MSWI) plants are an interesting source of raw materials because of their high annual mass flow of gold (Fig. 4).

The total flow of gold through incineration plants in Switzerland stands at an initial estimate of 1.3 tonnes per year,[17] with a theoretical value of CHF 65 million (2012: US$ 1 668.98 / oz tr)[13].



▶ **Fig. 4** MSWI residues: 1 Coarse slag > 5 mm 2 Finest slag < 0.7 mm 3 Fine slag < 5 mm 4 NF metal fraction < 5 mm 5 Electrostatic precipitator fly ash 6 Ferrous metal fraction < 5 mm 7 Kettle ash; Electronic waste: a Desktop computer b Consumer electronics (general) c Laptop d LCD TV e Printer f Photo / video camera g Mobile phone h CRT TV (11,16-19,26). Diagonal lines: Total amount of gold in selected geological sites, respectively the annual amount of gold from selected waste in Switzerland.

4. Environment

Gold mining by independent miners and small-scale mining (Artisanal and Small-Scale Gold Mining, ASGM) annually emits between 640-1 350 tonnes of mercury into the environment.[28] About 350 t of this is discharged into the atmosphere and 650 t into the hydrosphere via mine tailings or as contaminant in rivers, lakes, soils.[28] The resulting organic mercury compounds are highly toxic and pose an environmental risk and human health hazard.

Although the industrial extraction of gold from geological deposits is generally better regulated and controlled, it still has a significant impact on the environment. This is illustrated by, for example, the retention basins and waste dump area used for the mine waste from the "Golden Mile Superpit" in Kalgoorlie in Western Australia, which are significantly larger than the area of the open-pit mine itself.[10]

The gold content of 4.61 g / t[18] implies that about 215 000 tonnes of rock have to be moved and processed at the Golden Mile Superpit for each tonne of gold that is recovered (ecological rucksack). Based on an historical production of an estimated 1 800 tonnes and usable reserves of 500 tonnes[21] this means that almost 500 million tonnes of rock would have to be moved.

This waste from the mine is very heterogeneous and consists of ore, gangue host rock, metal, coal or fuel residues, loose sediment and mill residues, metallurgical slag, fly ash, process chemicals and fluids.[10] Heap leaching processes, which are are frequently used in large mines, not only extract the gold from the rock with cyanide, but often also liberate mercury, cadmium, uranium, lead and arsenic from the milled rock powder. This process requires on average 141 kg of cyanide per kg of mined gold, and the global use of cyanide in conventional gold mines is estimated to be 182 000 tonnes per year,[9] a part of which also ends up in the environment.

Abandoned mine waste dumps and tailings lead to air, soil and water pollution and pose a risk to ecosystems and people. For example, the processing of gold ore that contains arsenopyrite will also lead to a new environmental problem through the breakdown of the arsenic bound in the rock.[12]

The recycling of gold from waste has a different starting point; WEEE and MSWI slag pose a waste problem to society from the outset. The recovery of valuable materials under controlled conditions as well as the proper treatment and disposal (including removal of hazardous substances) of the remaining waste reduces the environmental impact.

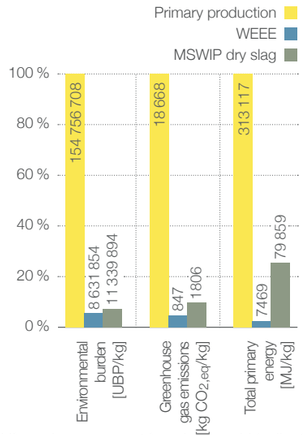


Fig. 5 Life cycle assessment for primary gold (yellow), as well as for gold from electronic waste (blue) or from MSWI dry slag (green), based on the environmental impact of the primary production (34). The environmental impact points (EIP) include energy consumption, emissions, land, water use, and landfills; GWP: cumulative effect of various greenhouse gases based on CO_2; Primary energy total: cumulative energy expenditure (renewable and non-renewable) for the entire delivery chain.

Compared to the primary production, the recycling of gold from MSWI slag and electronic waste brings significant environmental advantages (Fig. 5).[34]

5. Technology

Approximately 80-85 % of gold is mined on a large industrial scale under well-controlled conditions,[9] while the artisanal gold mining (ASGM), which is more difficult to regulate, yields the remaining 15-20 % (Fig. 6).

Artisanal gold mining often uses mercury (Hg) extraction for the following reasons:[28] Hg is a very effective extractant. Its high affinity to bind with gold (amalgamation) means that a single person can carry out the separation of the gold from the milled ore with minimal equipment and training. Hg is generally widely available, transportable and also very cheap to trade (for example, the mercury-gold price ratio in January 2008, was 1: 1650).

Industrial gold is mined from deposits in underground and open-pit mines or by dredging of unconsolidated sediments or old mill residues. The average currently mineable gold concentrations from important mines are around 3 g / t. Large sediment deposits (where free / pure gold is found in deposits: lower extraction costs) can be extracted to levels of 0.2 g / m3.21

Instead of extracting gold with mercury, industrial processes use cyanide, which is more expensive but more efficient (Fig. 6). The process can be summarised as follows: [21]

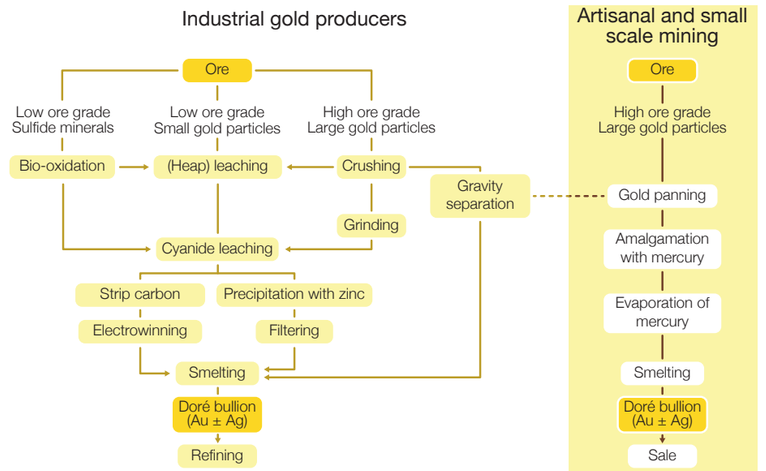


Fig. 6 Production of gold according to the industrial processes and in small-scale mining (30).

The gold is first extracted from the ore with a potassium or sodium cyanide solution (KCN or NaCN leach), bound with activated carbon filters, concentrated and purified through a melting process, which results in an economic recovery of concentrations, even with less than 0.2 ppm (g / t). The cyanide solution is only used if the ore contains extremely low percentages of S, Fe, Ag, As, Cd, Sb, Ni, Co and Zn since these elements would react with the cyanide solution. If these elements are present at a higher level, the ore must be pre-treated by means of flotation and roasting (oxidation), which in turn leads to higher costs and, consequently, a higher cut-off level (more losses).

6. Economy

The gold market is diffuse and characterised by speculative price fluctuations. The total market value of the annual gold production is in the upper range of all traded mineral commodities.[24]

The economic contribution of the gold industry in 2012 was estimated to be USD 110 billion, and gold mining yielded an estimated USD 78 billion for the fifteen largest mining countries. [35]

Alone the gold mining in Witwatersrand in South Africa, one of the world's most important gold deposits (gold content exceeds 5 g / t), employs over 145 000 people[35] and has significantly contributed to the economic success of South Africa with the excavation of over 50 000 tonnes of gold since 1884.[21]

With its 1040.1 tonnes of gold reserves in the Swiss National Bank,[37] Switzerland was ranked the seventh largest gold owner in the world in 2012; at around 180 g (2012: approximately CHF 9 600)[3] this equated to the highest national per capita gold reserve.

Furthermore, Switzerland is the most important global gold hub; four of the world's nine largest gold refineries are based in Switzerland and process more than a third of the yearly excavated raw gold:[9] The 2 299 t of gold[7] that were imported into Switzerland in 2012 had a value of approximately CHF 115 billion (2012: USD 1 668.98 / oz tr) (Fig. 7), while the total world trade was 4 453 tonnes (CHF 224 billion), of which 1 625 tonnes came from recycled sources.[36]

Commercial gold mining was only pursued in Switzerland until the early 20 th century (last gold mining activity was in 1939 at Astano) and due to social resistance and environmental concerns it is not possible, given the current circumstances.

The recycling of gold from anthropogenic waste streams, however, can be an economically viable operation in Switzerland; it is especially worthwhile for the individual components of waste electrical and electronic equipment (WEEE). Slag from municipal solid waste incineration (MSWI) plants also represents an economic potential for recycling; in addition to other metals, about 10 kg of gold[27] with a market value of CHF 370 000 (January-March 2014: CHF 1 150 / oz tr) can be recovered annually from the dry slag of the Hinwil MSWI alone.

It is also known that copper, gold, silver and palladium make up about 60 % of the non-ferrous metals in the dry slag at the Hinwil MSWI. The first three aforementioned can be suitably refined to a high purity and marketed at 80 % to 90 % of the world market prices.

The profitability of the material recovered from MSWI slag is further increased by the fact that it contains other recyclable metals that can be recovered at good conditions.

Fig. 7 Monthly gold prices from 2004 to 2014 (13). The shaded graph represents the difference between highest and lowest price, the brown line the month-end closing.