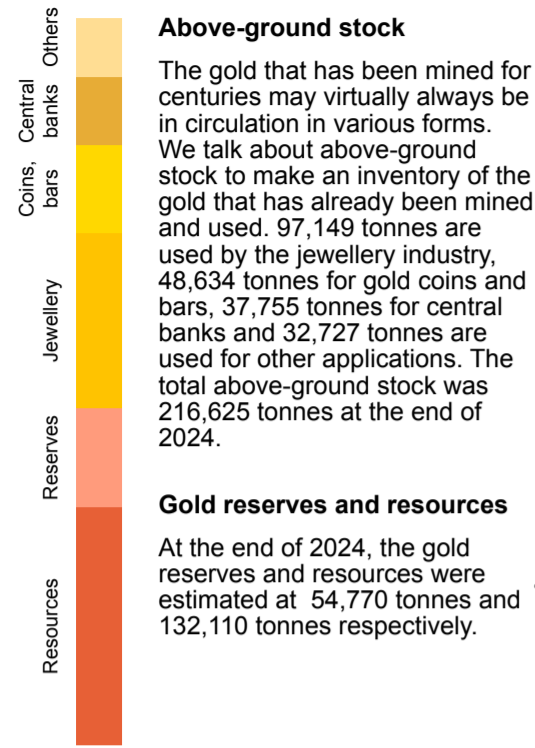
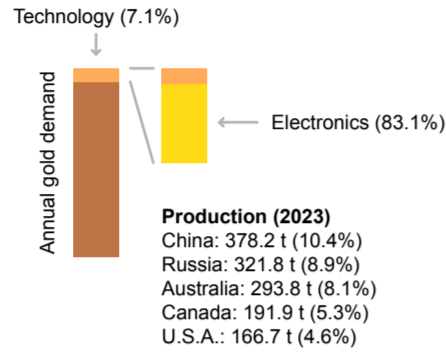


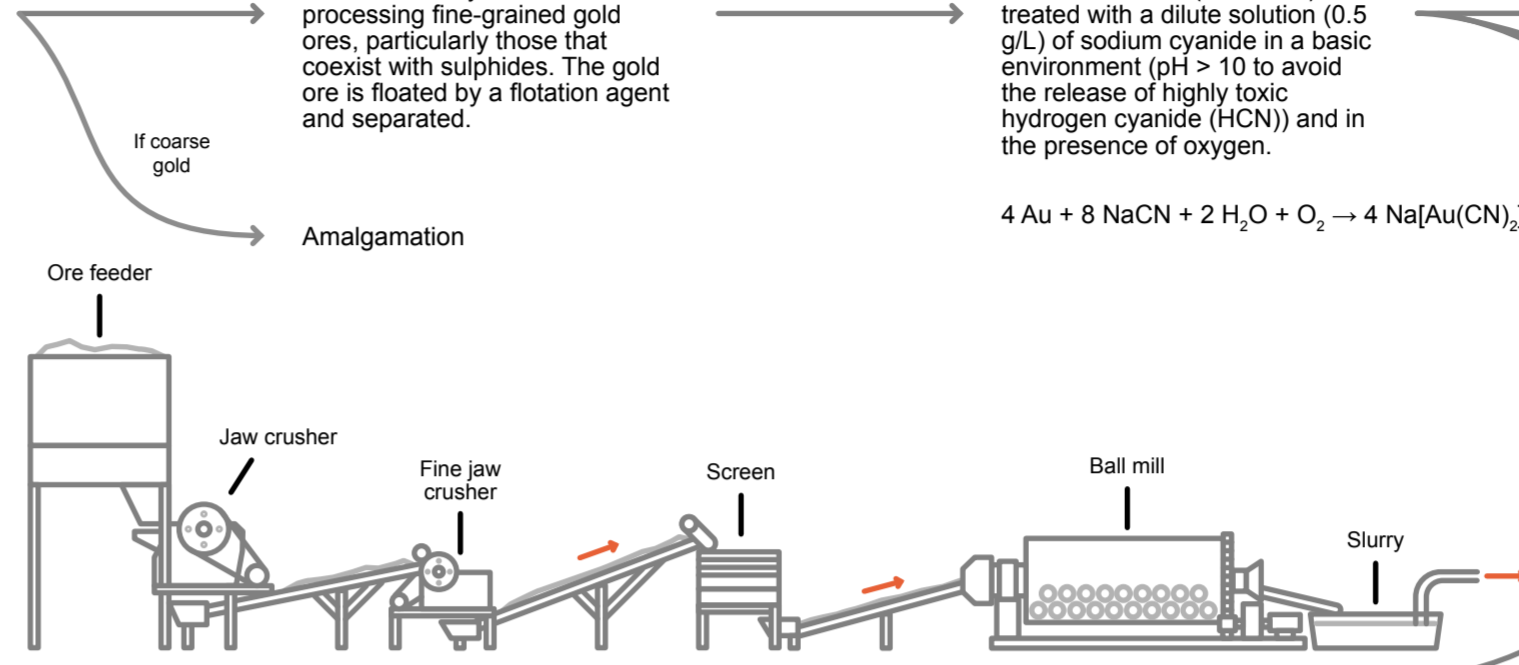
Supplementary Material 3 - Gold



Gold production
In 2024, 3,661 tonnes of gold were mined and 1,370 tonnes were recycled. 2,004 tonnes of gold were used in jewellery, 1,180 tonnes in investment, 1,045 tonnes for central banks, and 326 tonnes in technology. Of these 326 tonnes, 271 tonnes were used in electronics.



Crushing and grinding
The extracted ore is generally large and must be broken down into smaller particles by a crusher (jaw crushers and gyratory crushers for coarser particles; cone crushers and impact crushers for finer crushing). Grinding then consists of further grinding the crushed ore until a particle size suitable for the subsequent processing of the ore is obtained. The grinding process is generally carried out using equipment such as ball mills, rod mills or even wet mills.

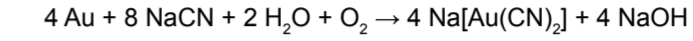


Flotation
Flotation is very effective for processing fine-grained gold ores, particularly those that coexist with sulphides. The gold ore is floated by a flotation agent and separated.

Amalgamation

Cyanidation is the most commonly used process, accounting for 80% of world production.

Cyanidation
The crushed ore (< 0.1 mm) is treated with a dilute solution (0.5 g/L) of sodium cyanide in a basic environment (pH > 10 to avoid the release of highly toxic hydrogen cyanide (HCN)) and in the presence of oxygen.

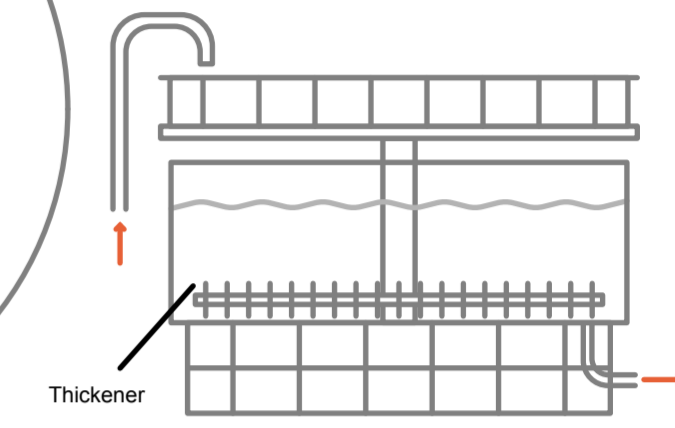


If ore contains a significant percentage of silver

Merrill-Crowe process (zinc cementation)

If ore contains active carbonaceous material

Carbon-in-Leach process (CIL)



Carbon-in-Pulp process (CIP)

Prescreening

The pulp is screened to remove the coarser materials such as wood chips that would block carbon granules in the circuit. Several types of screen are used: vibrating screens with woven wire or polyurethane mesh, linear moving-belt screens, and dummy tank.

Carbon adsorption

The pulp flows through a series of six or eight flat-bottomed cylindrical agitated tanks. The pulp spends about 1 hour in each tank. The last stage adds activated carbon, which is moved in the opposite direction of the pulp's flow. The carbon is held in each stage by screens that are placed between the tanks. The carbon spends one to two days in each stage. Between each tank interstage screens are used to retain carbon while allowing the finer pulp to flow down through the train. Carbon is moved upwards with pumps.

Elution

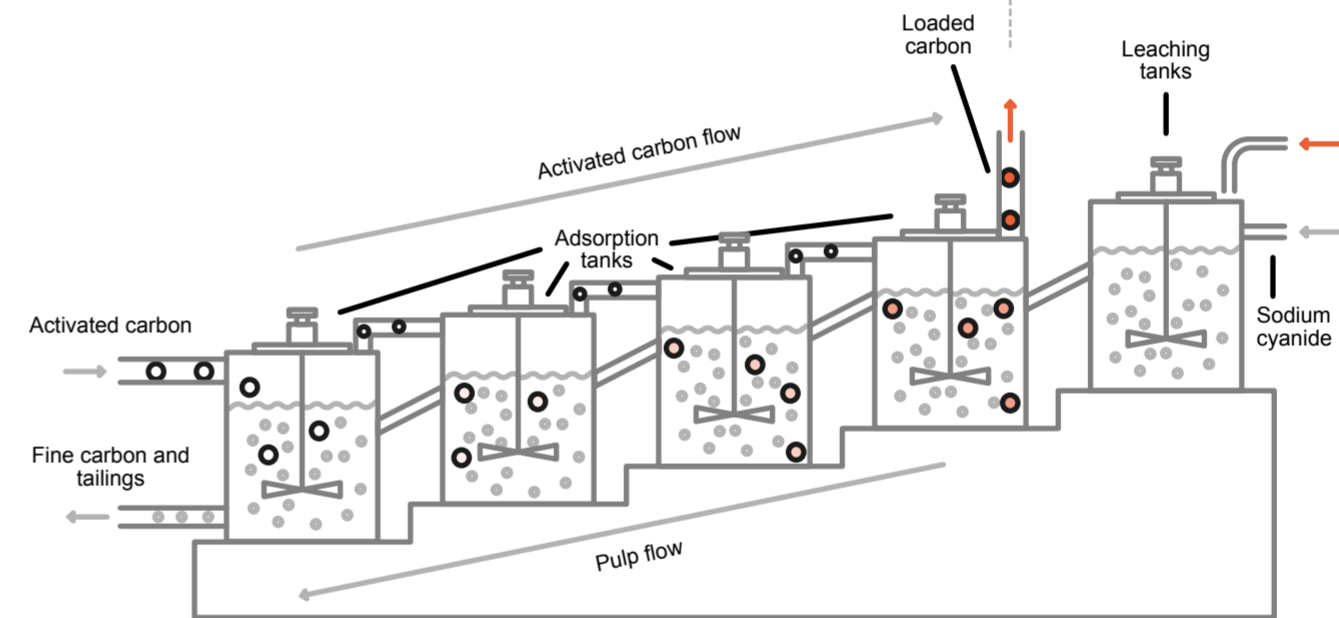
Elution (Zadra process) consists of recycling a solution containing 1 to 2% sodium cyanide and 1 to 2% sodium hydroxide through a bed of carbon. The temperature is above 85°C and the flow rate is approximately one bed volume per hour. Elution takes 48 hours.

Carbon regeneration

The loaded carbon is washed with a 5% solution of hydrochloric acid for 6 hours at 75°C. Reactivation is typically carried out at 700°C for 10 min. Regeneration is usually carried out in a rotary kiln.

If required purity is 99.5-99.6%

Miller process



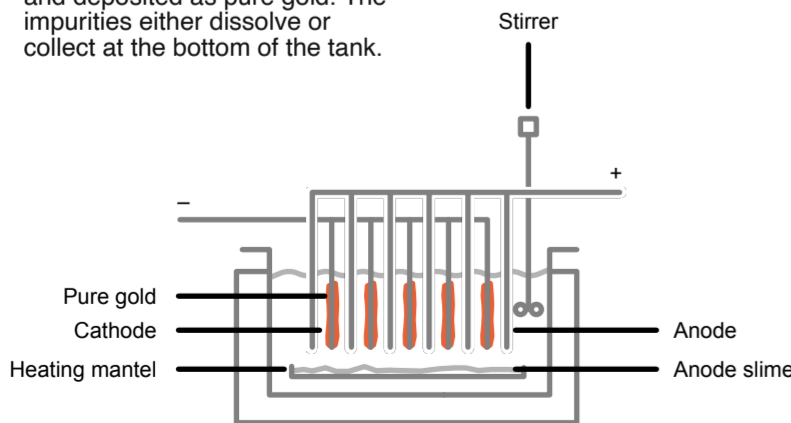
Before going in the electrowinning cell, the loaded carbon passes through an acid wash (elution) tank and a carbon stripping column.

Main refiners production capacity and production in 2023

- Vaicambi (Switzerland): 2,000 t capacity
- Argor Heraeus (Switzerland): 400 t (1,380 t capacity)
- Metalor Technologies (Switzerland): 650 t capacity
- Rand Refinery (South Africa): 600 t capacity
- MKS PAMP (Switzerland): 450 t capacity
- Heraeus Deutschland (Germany): 400-500 t capacity
- Tanaka PMT (Japan): 540 t capacity
- Johnson Matthey (UK): 250 t capacity
- MMTC-PAMP (India): 100 t capacity
- Umicore (Belgium): 100 t capacity
- PX Precinox (Switzerland): 60 t capacity
- Sumitomo Metal Mining (Japan): 60 t capacity
- The Great Wall Precious Metals (China): 20 t capacity
- Perth Mint (Australia): 244 t
- T.C.A. (Italy): 220 t
- Royal Canadian Mint (Canada): 187 t
- Navoi MMC (Uzbekistan): 80 t
- Mitsubishi Materials Corporation (Japan): 38 t
- Kazzinc (Kazakhstan): 17 t
- Almalyk Mining (Uzbekistan): 17 t
- Asahi Refining Canada (Canada): 11.7 t
- Met-mex Penoles (Mexico): 0.03 t
- United Precious Metal Refining (USA): Unknown
- Sempsa Joyeria Plateria (Spain): Unknown
- Solar Applied Materials Technology (Taiwan): Unknown
- ABC Refinery (Australia): Unknown
- C.HAFNER (Germany): Unknown
- Doduco (Germany): Unknown
- Heimerle + Meule (Germany): Unknown
- Hindustan Platinum (India): Unknown
- Italpreziosi (Italy): Unknown
- KGHM Polska (Poland): Unknown

Wohlwill electrolysis (electrowinning)

Electrowinning cells have a rectangular configuration with alternating anodes and cathodes in parallel. A casting of impure gold is lowered into a liquid mixture of hydrochloric acid (2.5 mol/L) and gold chloride (2 mol/L) agitated at 65 – 75 °C. The casting works as the anode and the cathode is made of pure gold. The current causes gold ions in the eluate to migrate to the cathode, where they are reduced and deposited as pure gold. The impurities either dissolve or collect at the bottom of the tank.



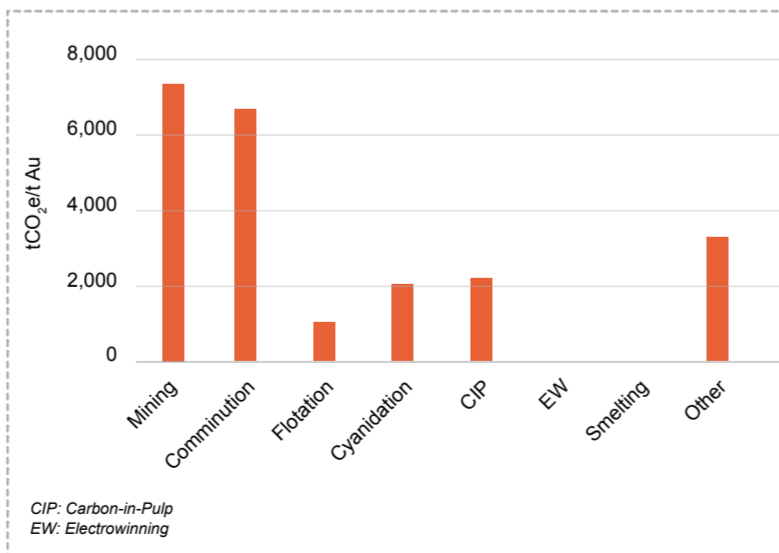
Smelting and refining

The cathodes are melted and cast in a smelting furnace with added fluxes to remove impurities.

Output

99.99% gold bullion bars or ≥ 99.99% gold pellets

Stage contributions to GHG of non-refractory ore extraction and refining (Norgate et al.)

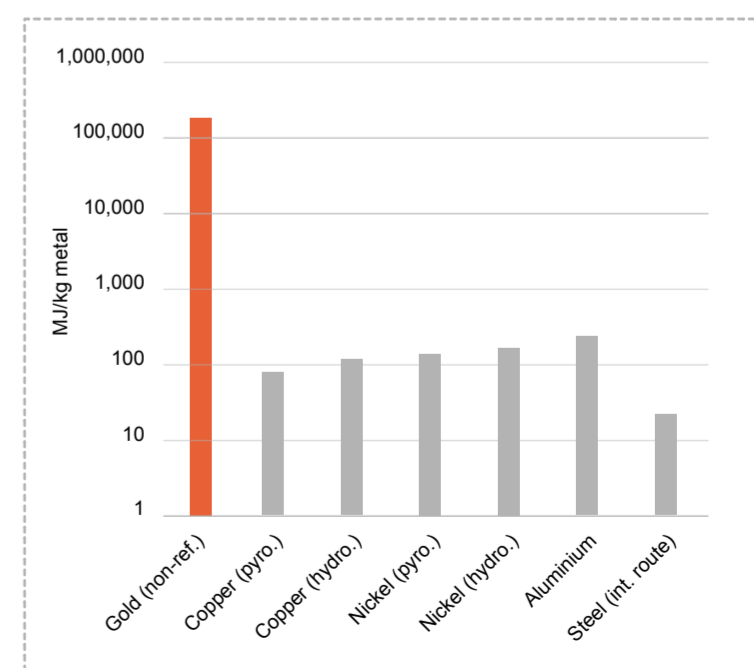


Inputs/outputs for the production of 1 t of non-refractory gold ore (Norgate et al.)

Process	Inputs	Outputs (simplified)
Mining	Diesel fuel (5.3 kg/t ore) Explosives (1.7 kg/t ore) Waste rock (3 t/t ore)	Pure gold (1 t) (≥99.99%)
Comminution	Electricity (17.7 kWh/t ore) Steel balls (0.71 kg/t ore) Electricity (3 kWh/t ore)	Energy (199,390 GJ/t Au) GHG (17,560 tCO ₂ e/t Au) Water (259,290 t/t Au) Solid waste (1,264,780 t/t Au)
Flotation	Reagents (154 g/t ore) Concentrate (0.1 t/t ore) Tailings (0.9 t/t ore)	
Cyanidation	Electricity (1.4 kWh/t ore) Lime (2.2 kg/t ore) Sodium cyanide (0.64 kg/t ore) Tailings (1 t/t ore)	
CIP	Electricity (5.8 kWh/t ore) Carbon (24 g/t ore) Sodium cyanide (0 kg/t ore) Sodium hydroxide (0.12 kg/t ore) Hydrochloric acid (83 g/t ore)	
Electrowinning	Electricity (3,100 kWh/t Au) Steel wool cathodes (0.25 t/t Au) Hydrochloric acid (0.49 t/t Au)	
Smelting	Natural gas (0.35 GJ/t Au - 6.6 kg/t Au)	
Miscellaneous	Fuel (0.3 kg/t ore)	
Refining	Electricity (8.6 kWh/t ore) Chlorination process (Electricity: 480 kWh/t dore - Chlorine: 0.07 t/t dore) Electrolytic process (325 kWh/t gold)	

Assuming an open-pit mine with a strip ratio of 3 t waste rock/t ore and ore grade of 3.5g Au/t

Comparison of embodied energy for gold production with other metals (Norgate et al.)



The environmental footprint of gold production (per tonne of gold produced) is several orders of magnitude greater than that for a number of other metals, largely due to the low grade of ores used for the production of gold compared to other metals.