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Sustainability and Climate Risk Analysis of Gold as a Central Bank Reserve Asset

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Gold is a precious metal with several functions: it has been widely used in jewellery for thousands of years, and, as it serves as a store of value and has other special financial properties, it is also used as an investment asset. Gold also plays a prominent role in central bank reserves, primarily as a safe-haven asset and diversifier. Climate change may have negative social and economic consequences, such as intensifying geopolitical tensions and rising inflation, which may increase demand for safe-haven assets, including gold. Considering the role gold plays in central bank reserves, it is important to understand its climate risk profile as well. In this paper, we assess the physical and transition risks of gold investments. The main message of our analysis is that gold as a final product is practically indestructible and therefore its physical risk exposure is negligible, but its transition risk profile cannot be clearly determined.

Journal of Economic Literature (JEL) codes: Q51, Q54, G32, E58

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1. Introduction

Exploring and understanding climate risks is a prerequisite for the green transition. The transparency of central banks is an important consideration also when climate risks are measured. As independent public institutions, central banks should assess the climate risks in their balance sheet because of the potential losses. Additionally, they can support the development of best practices in measuring climate risks and may also shape the climate awareness of market participants (*Kolozsi et al. 2022*).

* The papers in this issue contain the views of the authors which are not necessarily the same as the official views of the Magyar Nemzeti Bank.

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Accordingly, in recent years several central banks have emphasised the importance of the green transition and have made efforts to understand and disclose the climate risk exposure of their own operations and financial assets. The environmental sustainability and climate risk aspects of conventional financial investments (shares, bonds) are now widely discussed in climate-related financial disclosure reports published by central banks (e.g. *MNB 2024*). However, gold as a separate investment asset class has not been discussed so far, even though gold plays a prominent role in central bank reserves.

Awareness of environmental sustainability and other ESG (Environment, Social and Governance) issues is increasing on the gold market as well, as reflected in various market initiatives and the rising number of related analyses. When exploring climate change related risks, we must differentiate between physical gold as an investment and the gold industry. While participants in the gold market are closely interconnected as far as market effects are concerned, climate change processes may have different impacts on companies at different stages of the supply chain.

The carbon footprint of gold mining has been estimated in various studies, including *Ulrich et al.* (*2020*). The World Gold Council (WGC), the international trade association of the gold industry, has also published analyses of the connection between gold and climate change, the adaptation and decarbonisation options of companies involved in gold mining (*WGC 2018, 2019a, 2021a*) and the economic and social impact of WGC member companies (*WGC 2021b*). Various approaches have been used in the literature to analyse the environmental impact of gold mining. Both regional (*Chen et al. 2018*) and global mining data (*Mudd 2007*) have been researched. The carbon intensity of gold mining is analysed in comparison to other metals in some studies (see *Nuss – Eckelmann 2014*) and from the aspects of the extraction process in other papers (*Norgate – Haque 2012*). In addition to carbon intensity data, *Ulrich et al.* (*2022*) also analysed the impact of the introduction of a global carbon tax.

Our paper aims to contribute to the literature by integrating gold investments into the existing framework of central bank climate risk analyses as a separate asset class. We seek to answer the question how the environmental sustainability aspects of investment gold can be explored in the context of central banks' FX reserves. As the significance of climate risk considerations is increasing in the financial sector as well, it has become necessary to examine this precious metal, which has been popular for thousands of years, in terms of the new aspects that have emerged in the evolving investment environment. Gold as a special commodity has several unique properties that make the analytical approaches used for conventional financial assets difficult to apply. Methodological challenges and the need to meet the new expectations of investors make the focus issue of the paper very topical.

In the first part of the paper, the interpretation context, i.e. the historical role of gold in financial markets, is described. This is followed by the analysis of how the emissions impact of gold investments can be compared to the profile of other financial products, and what risks lie, with respect to existing gold investments, in the economic and social processes expected to be triggered by climate change.

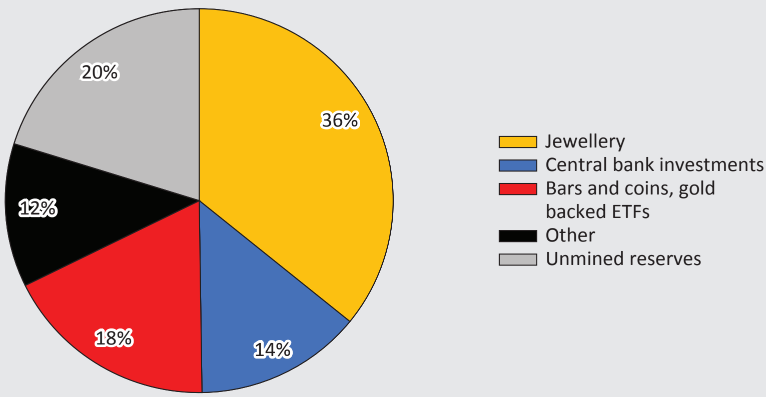
2. Gold as an investment asset

2.1. The role of gold in financial markets

Historically, gold has been among the most sought-after precious metals, a symbol of purity and nobility. Gold has several functions: it has been widely used in jewellery for thousands of years, and it is also used in modern industry. In addition, it serves as a store of value and is thus an investment asset (*Bánfi – Hagelmayer 1989*).

According to current estimates, approximately 216,265 tonnes of gold has been mined over the course of history, and about two-thirds of that has been extracted since 1950. Underground reserves are estimated at 54,770 tonnes (*Figure 1*).

Figure 1
Distribution of stock of gold (end of 2024)

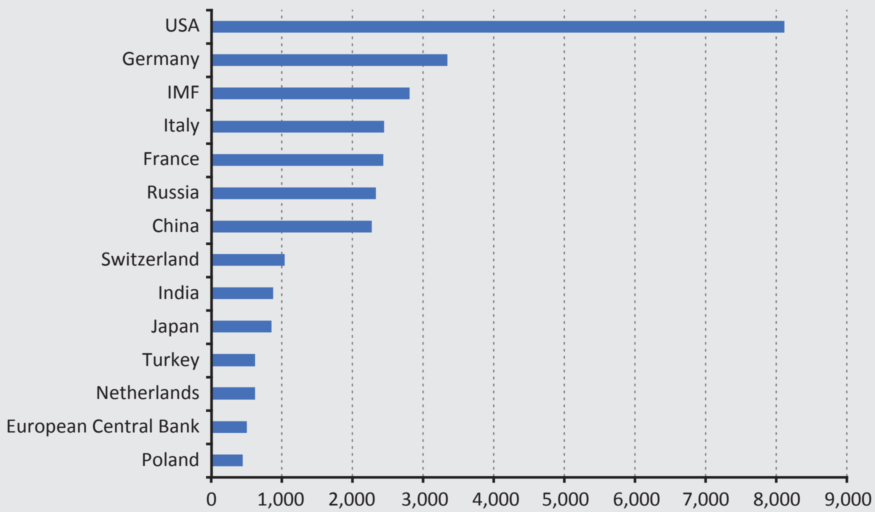


Source: Compiled from data by WGC (https://www.gold.org/goldhub/data/how-much-gold)

Throughout history, gold has been a central element in financial systems: it was first used as commodity money (*Bánfi 2022a*) and then in the 19th and 20th centuries countries around the world tied the value of their currencies to gold under the gold standard system (*Lőrincné Istvánffy 2004; Bánfi 2022b*). After World War II, until the collapse of the Bretton Woods system in 1971, the tying of the US dollar to gold was at the centre of the financial system: parties to the agreement guaranteed that their currencies would be pegged to the US dollar, and a fixed-rate conversion between USD and gold was also agreed (*Hagelmayer et al. 1975*).

While gold's significance in the operation of financial systems has decreased in recent decades, it still plays a prominent role (*Banai et al. 2021b*). This is clear from the exposure of central banks to gold, as after the US dollar and the euro, gold is the third most important reserve element, amounting to about one-fifth of global reserves. Despite the collapse of the Bretton Woods system, several countries still hold significant amounts of gold, with the USA, Germany and Italy having the three largest reserves (*Figure 2*).

Figure 2
Largest official gold reserves (tonnes, end of 2024)



Source: Compiled from data by World Official Gold Holdings and International Financial Statistics

Not immediately after Bretton Woods but in the 1990s, central banks' approach to gold in developed countries changed significantly, leading to a moderate decrease in gold reserves (*Palotai – Veres 2020*). Central banks with substantial gold reserves wanted to diversify away from gold without jeopardising the value of their existing portfolios. Relevant agreements were made on these issues, and the Central Bank Gold Agreement (CBGA) was signed in 1999 and then renewed three times. The role of gold was less prominent in reserves than it was in the Bretton Woods system.

This trend came to an end with the global financial-economic crisis in 2008: developed countries practically stopped selling gold, while emerging countries started to buy more, which led to a general increase in gold reserves. The low-return environment of the 2010s, i.e. the decrease in the opportunity cost of holding gold, and the increasing significance of the safe-haven function also played a role in this. This change in the trend is also shown by the fact that the CBGA was not renewed by the signatories when it expired in 2019 (*ECB 2019*), and more and more central banks are currently appearing on the gold market as buyers (*Ladányi – Paulik 2018*).

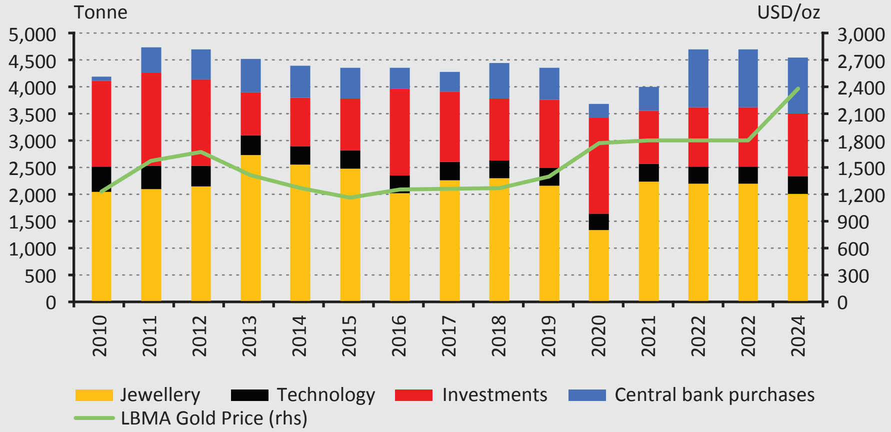
2.2. Special features of gold investments

Analysis of the dynamics of supply and demand on the gold market reveals the dual nature of gold: on the one hand, it is a commodity with physical demand and supply from mining (and recycling), while on the other it is also a financial-investment product where, in addition to buying and holding physical gold, derivative markets may also affect market conditions. The gold derivatives market is extensive, with a significant trading volume in both OTC and exchange-traded futures, but investors can also gain exposure though ETFs. The liquidity of the different markets is high. However, there may be a considerable price spread across markets.

Gold's prominent role is clear from the global volume of central bank gold reserves, which exceeds 36,000 tonnes,[1] as well as from the fact that recent purchases by central banks and other investors have accounted for nearly one-half of annual demand (*Figure 3*).

[1] Value exceeding USD 3,000 bn, at 2024 end-of-year prices

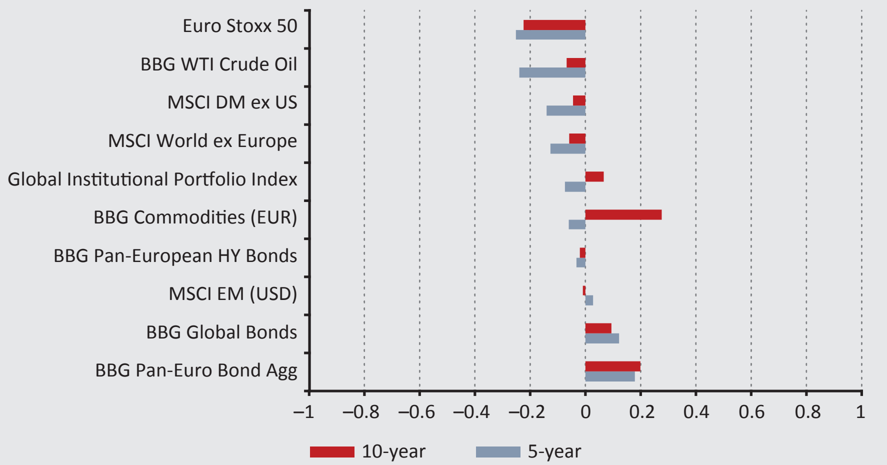
Figure 3
Breakdown of annual demand for gold and the price of gold



Source: Compiled from data by WGC (https://www.gold.org/goldhub/data/gold-demand-by-country)

The price of gold depends on a number of factors (*Asztalos – Asztalos 2011*). Historical experience shows that the co-movement of the prices of various investment assets increases as the uncertainty of the market intensifies. The weak correlation between gold and other asset indices (especially in turbulent times) substantiates the idea that gold can have a diversifying role in investment portfolios over the medium or long term (*Figure 4*).

Figure 4
Correlation between gold and other asset classes



Note: For the periods 31 December 2014 – 31 December 2024 and 31 December 2019 – 31 December 2024, based on monthly returns.

Source: Compiled from data by WGC (https://www.gold.org/goldhub/data/gold-correlation)

The safe-haven[2] status of gold has been explored in several empirical studies (e.g. *Bouoiyour et al. 2018*). Some of these analyse the connection between the price of gold and geopolitical risks (*Baur and Smales 2018; 2020*) or the price of gold and pressure on global supply chains (*Li et al. 2023*), while others (*Gosh et al. 2001; Beckmann – Czudaj 2012; Conlon et al. 2018*) point out that gold may also be useful as a hedge against unexpected inflation.

Overall, it can be established that gold investments have a number of special properties (*Arslanalp et al. 2023*): gold is an investment which is independent of the issuer and can be stored in any country,[3] which means it is a store of value with practically no credit risk; its price typically rises in times of market stress (flight-to-quality effect), which may be of particular importance from a central bank perspective in the event of an increase in both geopolitical and financial risks; depending on the investment horizon, it can help mitigate the negative effects of unexpected inflation. It is also important to note that the gold market is regulated, structured and deep,[4] and when necessary, physical gold can be converted to liquidity in other currencies through various swaps.[5]

Considering the events of the past 10–15 years (e.g. Lehman crisis, the European sovereign debt crisis, Brexit, Covid, Russia-Ukraine war), these properties may counterweigh the other financial and investment considerations that arise in relation to gold (e.g. no interest payment, relatively high price volatility compared to bond investments, potentially lower liquidity of physical gold) and explain the renewed interest of central banks. Fears of potential international sanctions and an intention to move away from the US dollar may have been among the factors considered by several larger countries when buying gold (*Alimukhamedov 2024*), while central banks in other countries (e.g. Hungary, Czechia, Poland) decided to increase their gold reserves considering strategic aspects and emphasising the positive features of gold (*Banai et al. 2021a; Veres 2024*).

[2] In the case of gold, the safe-haven feature is also reflected in the positive skewness of the returns, as opposed to the negative skewness of other assets (*Lucey et al. 2003*).
[3] No significant extra costs are incurred when it is stored in own existing vaults (used for other purposes as well, e.g. for storing cash).
[4] The average total daily trading volume of gold across various platforms (OTC, stock exchange, ETF) exceeded USD 162 bn in 2023, which is comparable to US T-bills (USD 161 bn) and the EUR/GBP market (USD 154 bn). (See https://www.gold.org/goldhub/data/gold-trading-volumes)
[5] Converting electronic gold to liquidity is easy through account movements. Liquidity is more limited when gold is stored or held physically, far from large financial centres.

3. Assessment of the climate risks of gold as a separate investment asset class

Investors increasingly combine conventional return-risk goals with other, non-financial aspects (*MNB 2023*), as reflected in the increasing interest in sustainable and responsible investments.[6] It should be noted that investor demand for gold and the weight and role of gold in a given portfolio are basically determined by strategic and financial aspects; central banks' demand is also primarily driven by the favourable properties of gold as a diversifier or safe-haven asset. However, it is important to realise that various climate scenarios (e.g. by NGFS) predict an increase in geopolitical tensions and inflation risks, disruptions to agricultural production, GDP declines and potential disruptions to the financial system (*NGFS 2024*). This means that climate-related considerations may affect investor decisions indirectly rather than directly, for example as tail risk events that spill over to the conventional analytical framework through various transmission channels.[7] Taking this into consideration along with gold investments' global scale and significant role in the reserve portfolios of central banks, it seems appropriate to try to understand the sustainability and climate risk aspects of gold.

With regard to conventional investment assets, based on the double materiality principle, climate risk analyses provide, on the one hand, assessments of the extent to which the operation of the issuer of a security (company or state) contributes to processes driving climate change (e.g. GHG emissions) and how and to what extent this is financed by investors (impact approach). On the other hand, such analyses also explore how the consequences of climate change (physical and transition risks) may, in turn, affect the issuers' operations and the value of their securities (risk approach).

This concept can be applied to gold as well, with the difference that climate risks may be assessed with two different approaches: gold can be considered as exposure to an industry, and companies in the value chain of the gold industry can be analysed (as for bonds and shares); however, it must be taken into consideration that gold is also a physical commodity.

[6] Sustainable and Responsible Investments (SRI)

[7] It should be noted that as global warming increases, the probability of events once considered extreme increases every year.

It is important to note that the assessment of environmental sustainability and climate risk aspects is not only relevant for central banks that intend to buy gold, but also for those that hold existing stocks, as the value of their investments is ultimately determined by the price of gold on the secondary market, which, through prevailing supply and demand conditions, may be affected by processes potentially triggered by climate change.

3.1. Assessment of physical risks

Physical risks arise from the increase in the severity and frequency of extreme weather events (e.g. extreme heat or cold, drought, tropical cyclones, coastal flooding, river flooding, forest fires, supercells, flash floods). In this category, it is not only the risk of losses due to the physical deterioration of assets and infrastructure that is considered, but also the breakdown of value chains, loss of biodiversity and the degradation of ecosystem services, which may have negative impacts on human health and well-being, and may spill over to the economic-financial system through transmission channels.

Physical gold is practically indestructible: it is not damaged even during (climate) disasters, which can be a positive feature compared to other investments – in specific companies – as physical risks may have a serious impact on the operation of such companies. Obviously, during a climate disaster, accessing, transporting and guarding gold may pose a challenge, but this is a problem of a completely different scale, time horizon and cost implications.

In the case of bond investments, physical risks are often analysed as supply-side shocks (e.g. a production facility is destroyed). According to this approach, in the case of gold the investor takes a position vis-à-vis an entire industry, not a specific company, which represents a significant difference compared to bond or equity investments; this is comparable to an ETF replicating a broad bond market index. Climate change may negatively affect certain participants involved in gold production, but the supply and demand shocks experienced, for example in the oil market, are considerably less likely to occur in the case of gold (*Fazekasné Szikra – Pivarcsi 2017*). This is basically because the geographical distribution of existing gold reserves is less concentrated (*Table 1*).

Table 1
Share of industrial gold mines in production

Annual production [tonne]	Share of gold mines (locations) (%)	Share of global production (%)
≥ 10	7	39
5 ≤ < 10	14	26
1 ≤ < 5	47	31
< 1	32	4

Note: The table shows the data of 622 industrial mines (2018–2021); mines producing gold as a by-product and small-scale producers are not represented.
Source: Compiled by Schütte (2023) based on data by S&P Global

In the case of gold, no region accounts for more than one-fifth of global production, which means more stable supply conditions, i.e. problems that may occur in some places do not necessarily lead to global supply shocks (*Figure 5*).

Figure 5
Geographical location of gold mines with the largest annual production volumes

Note: Mines with annual production exceeding 10 tonnes in at least one year between 2018 and 2021.
Source: Compiled by Schütte (2023) based on data by S&P Global

Another significant difference is that while a disruption in the operation of a specific company (due to the materialisation of physical risks) typically worsens the performance of the given company, industry or even the entire index, in the case of gold, extreme weather conditions may even lead to price increases due to the temporary decline in supply, which increases the value of existing investment positions.

Based on the above considerations, it can be concluded that the physical risk exposure of the gold reserves is relatively low compared to other forms of investment, and the realisation of risks may, in certain scenarios, even increase the value of the investment.

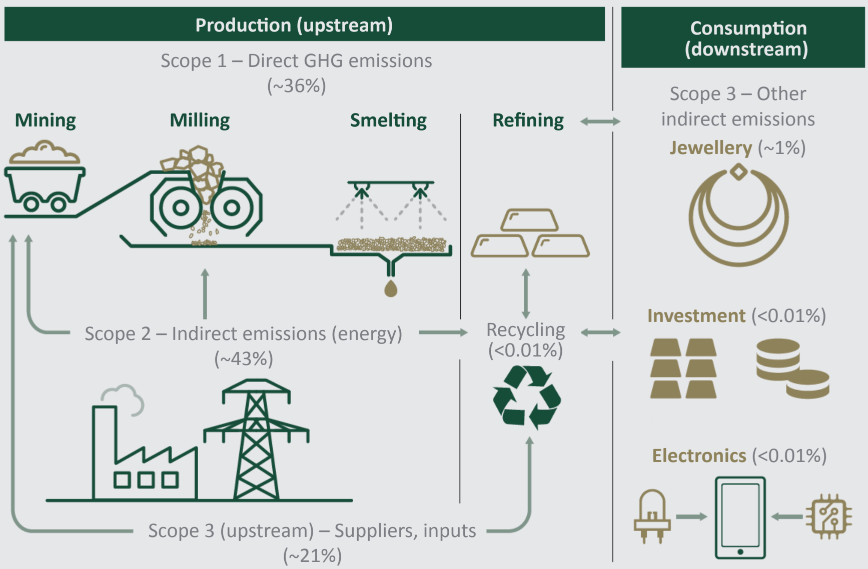
3.2. Assessment of transition risks

3.2.1. Emissions profile of the gold industry's value chain

Transition risks arise from the challenges of transitioning to a low-carbon and climate change resilient economy. Policy (e.g. more stringent emissions requirements, quotas, carbon tax, etc.), technological changes and rapid changes in consumer attitudes can all cause sudden changes in the price of financial instruments. As a consequence, credit and market risks may increase, and in certain scenarios, the resulting losses may spill over to the whole economic-financial system.

To understand transition risks, first the emissions profile of the gold industry's value chain must be explored. The production process has four main stages: mining, milling, smelting and refining (*Figure 6*).

Figure 6
Process and GHG emissions of the gold industry's value chain

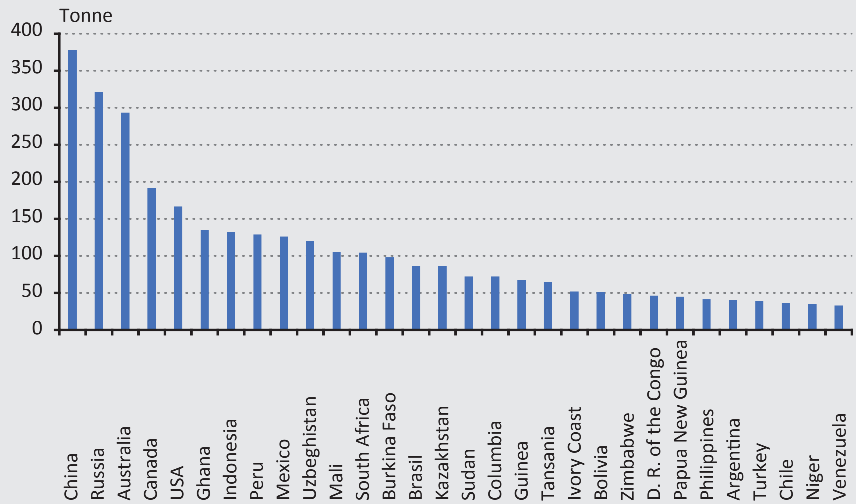


Source: WGC (2019a, p.11)

The annual emissions of the gold industry are estimated at approximately 120–130 million tonnes of CO_2e, which is only 0.25–0.3 per cent of the total global emissions, but is by no means negligible. The vast majority of production (approximately 80 per cent) comes primarily from gold mining companies using large-scale technology, most of which are listed companies, with a smaller proportion coming from small-scale mining. The emissions profiles of mines are highly heterogeneous and are determined by a number of factors (type and depth of mine, technology, grade of ore, etc.), but it is clear that the separation of gold from ore accounts for a large part of the value chain's energy demand, the vast majority of which is related to the use or on-site generation of electricity (*WGC 2019a*).

Considering that the energy mix of grid electricity varies by region, the gold's place of origin must be identified for the assessment of the emissions profile. Until 2006, South Africa was the largest gold producer globally. After 2007, production increased in other countries and decreased in South Africa,[8] and China became the top gold-producing country. In 2023, the countries with the largest gold production (China, Australia and Russia) accounted for approximately one-third of total global gold mining (*Figure 7*).

Figure 7
Production of the top 30 gold mining countries (2023)



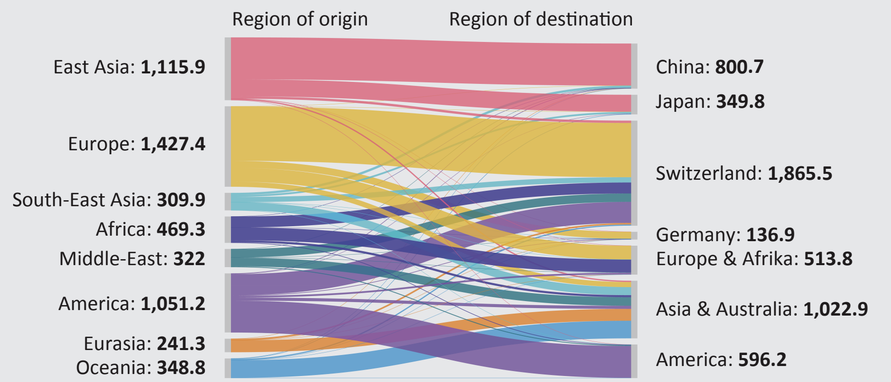
Source: Compiled from data by the WGC (https://www.gold.org/goldhub/data/gold-production-by-country)

[8] Mining in old mines is no longer profitable, as these are very deep and the concentration of gold in the ore is low.

Polluting energy sources still play a significant role in the energy mix of several top gold-producing countries,[9] whose future climate goals are not very ambitious.[10] This means the transition to carbon neutrality is a challenge for the gold industry as well, but it must be noted that – as opposed to other sectors (e.g. aviation, maritime transport) – the technological aspect of decarbonisation is relatively easy, for example with the installation of renewable energy sources. Accordingly, more and more of the largest participants in the industry are preparing medium-term decarbonisation plans (*WGC 2020*).

While most gold-related GHG emissions are generated during extraction, it is also clear that after it is mined, gold is transported across the globe, which also has an impact on the climate. Country of origin data from LBMA[11] provide an insight into the global physical flows of gold – from the country or region of origin, where the Good Delivery List (GDL) Refiners source their feedstock, to the country of destination, where the material is refined (*Figure 8*).

Figure 8
Global gold material flow (2022, tonne)



Source: Compiled from data by LBMA (https://www.lbma.org.uk/country-of-origin-data)

While there is an overlap between the countries producing and countries using the most gold (e.g. China), there are several destination countries with no gold production whatsoever (e.g. Germany, Switzerland, Japan). In this context, it should be noted that the share of recycled gold is high in practically every region (recycled gold amounts to approximately one-quarter of annual supply).

[9] https://www.iea.org/data-and-statistics
[10] https://climateactiontracker.org/countries
[11] The London Bullion Market Association (LBMA) is an international trade association operating the OTC wholesale market of gold and silver, accounting for approximately 50–60 per cent of the total OTC trading volume. LBMA sets strict standards for the purity, shape, size and quality of gold and silver bars on the market. It also administers the London Good Delivery list, a list of accredited refiners whose bars meet LBMA standards.

3.2.2. Emission of the gold industry in light of specific indicators

In order to understand the impact of gold as an investment product on climate change, and its climate risk exposure, it is first necessary to examine widely-used emissions intensity ratios, which, in the case of gold, may include the following:

- *tCO_2e/tonne of ore: emissions intensity of processed ore per tonne, which helps the assessment of the absolute change in GHG emissions in the case of mines with steady production. This, however, is not very useful for the comparison of mines unless they have the same nominal ore processing capacity.*
- *tCO_2e/tAu: specific GHG emissions of the final product, the best for the comparison of extraction companies or specific mines.*

Emissions estimates per tonne of gold vary widely in the literature (11,500–55,000 tCO_2e/tAu), mainly due to differences in the energy mix of the regional electricity grids. *Nuss – Eckelman* (*2014*) gathered data on the environmental impact of 63 industrial and precious metals and demonstrated that the environmental impact per kilogram is the highest for the platinum group and gold. *Haque – Norgate* (*2014*) estimated, among others, the GHG footprint of gold (38,100 tCO_2e/tAu). *Ulrich et al.* (*2020*) used gold mining data from Australia to analyse the connection between the quality of gold ore and GHG emissions per ounce. In another study (*Ulrich et al. 2022*), they aggregated mine-specific GHG emissions and production data at the country level, allowing for the quantification of the effects of a potential global carbon tax. There is also additional research in the literature that addresses other environmental impacts of gold production. *Chen et al.* (*2018*) analysed the environmental impact of gold production in China through a life cycle assessment. *Norgate and Haque* (*2012*) found that the broadly defined environmental footprint of gold production (per tonne of gold produced) was several orders of magnitude greater than that for a number of other metals, largely due to the low grades of ore used for production. They estimated GHG intensity (18,000 tCO_2e/tAu) and other environmental impacts, including use of water per tonne (260,000 tH_2O/tAu) and remaining solid waste for non-refractory ore (1,270,000 *t/tAu*).

3.2.3. Environmental impacts from an investor's perspective

When analysing the environmental impact and climate risks of financial investments, it is necessary to examine the extent to which the investment contributes to financing emissions (see financed emissions, GHG Protocol – Scope 3 Standard), and the potential impacts of climate change processes on the value of investments. Investors finance GHG emissions involved in the activities of the issuer of a security through their ownership interest in the case of shares and as creditors in the case of bonds.

In international practice, there are several approaches for assessing the environmental impact (and climate risks) of conventional investments. According to the recommendations of the TCFD,[12] these include the carbon intensity ratio[13] calculated as the ratio of the annual GHG emissions resulting from the production and the corresponding annual revenue or the value added[14] generated by the given sector or company. The indicator shows how efficiently, from an environmental perspective, the issuer generates value added, and it is also used as a proxy for transition risks, for example as the basis for estimating how a potential carbon tax (or any other regulatory restriction affecting emissions-intensive activities) may directly impact the operations of a given company or industry. The advantage of this indicator is that it is relatively easy to calculate and does not require a complex methodological background. However, its disadvantage is that it relies mainly on historical data, i.e. it does not take into account possible future decarbonisation paths, nor does it provide answers as to how a given industry or company can adapt, for example, to what extent it can pass on the cost shock to other actors in the value chain.

The same logic may be applied to gold as well: calculated as the ratio of the annual value added of the gold market and total generated emissions, carbon intensity is approximately 400–600 *tCO_2e/million € value added.*[15] The question arises as to how this can be compared to other industries. Industry intensity ratios vary across and within countries. For example, in Hungary, 250, 470, 1,000, 2,140 and 7,130 *tCO_2e /million € value added* is generated in construction, manufacturing, transportation, agriculture and energy supply, respectively.[16] Based on this, it can be concluded that the carbon intensity of the gold industry is relatively favourable, primarily due to the high value of gold.

In addition to gold, central bank reserve portfolios mainly consist of sovereign bond exposures, and accordingly it is worth comparing these as well. For the first time in 2023, the eurozone central banks published their climate risk disclosures using a unified methodology. Among other data, they presented the weighted average carbon intensity of their portfolios, which varied between 150 and 350 *tCO_2e/million € GDP* (see *Marczis – Karácsony 2024*).[17]

The indicators for gold and bond portfolios are of similar magnitude, but attention should be drawn to a difference in methodology that calls for the use of an

[12] Task Force on Climate-related Financial Disclosures
[13] Weighted average carbon intensity (WACI). The indicator quantifies the average carbon intensity of portfolios, weighted with the share of the assets in them. For more on this indicator, see *Marczis – Karácsony* (*2024*).
[14] Either Enterprise Value Including Cash or market capitalisation; in the case of sovereign bonds, annual GDP.
[15] The exact value is highly affected by the gold price used, e.g. end-of-year price or annual average price.
[16] Eurostat Air Emission Accounts, 2023
[17] The basis of calculation is somewhat different for corporate and sovereign WACI (earnings, GDP, value added), which might lead to a slight distortion, but does not affect the interpretation context.

alternative approach: shares and bonds finance the current and future operations (and related emissions) of companies, and therefore the corresponding WACI represents continuous, annualised emissions and value added, which are meant to be used as a basis of comparison for those investing in the shares and bonds of companies in the gold industry. On the other hand, in the case of physical gold investments, the gold bars purchased only had a GHG impact once (during production), and no significant recurring emissions arise as they are held. The question is if and how the emissions aspects of physical gold can be integrated into the interpretation framework used for bonds and shares.

Some (*Baur – Oll 2017*; *WGC 2018*) suggest that, instead of intensity ratios (e.g. WACI), the focus should be on total carbon emissions (TCE). For companies, annual nominal GHG emissions (tonnes of CO_2e) can be determined, and where applicable, it can also be established how much tree planting or annual carbon credit purchases are required to offset this. The amount of GHG emissions generated during production can also be estimated for physical gold (approximately 11,500–55,000 tCO_2e for 1 tonne of gold). Given that gold generates a one-time emission, in the case of offsetting, it is necessary to determine the period over which such compensation is to be provided.[18] *Baur – Oll* (*2017*) examine how the climate impact of a gold investment of USD 1 million compares to a similar investment in the S&P500 stock index. To ensure comparability, the one-time GHG emission of gold is divided by the expected holding period of the investment: the longer the time horizon over which the single GHG emission can be spread, the lower the annualised value of the indicator. In their analysis, they conclude that regarding the emissions impact of gold – depending on whether the minimum or maximum value of the estimated range is used – the "break-even point" is reached in 4 to 9 years, meaning that in this approach the climate impact of gold is more favourable in the life cycle assessment if the investment period is long enough.

When conducting analyses related to gold, it is important to consider the position of the given investor: before making new investments, a number of ESG factors can be examined (screening), including the emissions impact of the purchase compared to other assets. However, in the case of existing portfolios, alternative questions need to be asked, as the environmental impact of previously purchased gold is a past condition. In its climate risk report, the German *Bundesbank* (*2024*) formulated the question of what the hypothetical annual carbon impact of its gold reserve would be if it had been produced today.[19]

[18] It is estimated that it takes 31–46 trees to absorb 1 tonne of CO_2e annually (see encon.eu), i.e. to offset the emission of 1 tonne of gold, approx. 250–1,774 trees need to be planted if the total impact were to be offset over the course of one year.

[19] Amounting to 3,353 tonnes, which was accumulated between 1950–1970 and has been held since then.

3.2.4. Transition risks from an investor's perspective

When analysing transition risks, it can generally be said that any regulatory changes introduced to promote the green transition have a negative impact on companies engaged in carbon-intensive activities, for example by making production more expensive, reducing profitability, making it more difficult to access funding and providing a competitive advantage to other companies with greener technologies. As a result, the value of an investor's shares or bonds usually decreases. However, in the case of gold, this interrelation is not clear-cut. It can be stated with certainty that there are no direct effects with regard to physical gold already held in the portfolios, and thus the direct effects of transition risks can be considered marginal.

Taking into account that the value of existing gold investments is also determined by the gold price, which is shaped by prevailing market supply and demand conditions, indirect effects may also play a significant role. However, estimating such indirect effects poses a number of challenges, as it is unclear how regulatory changes or consumer preferences may affect supply and demand. As shown above, as a result of the negative socio-economic processes triggered by climate change, on the one hand, demand for safe-haven assets may increase, but a scenario is also possible where more stringent regulations imposed on emissions-intensive industries are reflected in the cost of production, which – via the increase in prices – may even improve the position of investors who already have gold exposure. However, it is also possible that investors start preferring gold bars that were mined according to more stringent environmental rules,[20] which may have a negative impact on the price of gold.

It is important to note that a significant number of central banks hold their gold reserve in physical form. In addition to these challenges, the climate impacts of gold derivatives are even more difficult to identify, as these are not necessarily linked to physical gold.

4. Environmental sustainability and ESG in the context of gold

Gold mining may involve both positive and negative externalities. Effects are positive if a certain activity contributes to the well-being of local communities as well, for example gold mining creates jobs and the company contributes to the financing of local schools and healthcare institutions. It is important to note, however, that various ESG risks may be associated with gold mining,[21] mostly linked to topics such as water management, natural capital, waste management, air pollution and social risks.

[20] Some gold ETFs already take this into consideration (see *Alimukhamedov 2024*).
[21] Mostly in the case of small-scale mines accounting for 20 per cent of global production

4.1. Industry standards

Although gold investments by central banks are fundamentally driven by strategic and financial factors, due to the increasing importance of environmental, social and sustainability considerations in the attitudes of investors (e.g. UN Principles for Responsible Investment) and consumers, players in the global gold market are giving more and more weight to the aspects of responsible sourcing and use.

This was one of the factors that motivated WGC and LBMA to issue the gold industry's *Declaration of Responsibility and Sustainability Principles.*[22] Signatories set ten key sustainability goals, which include aligning with responsible sourcing standards, supporting the advancement of the UN Sustainable Development Goals,[23] and stepping up against climate change and committing to reporting. They also agreed to report their progress in the implementation of these principles in a transparent manner. Additional standards were developed for the various stages of the value chain: for mining, it is the World Gold Council's *Responsible Gold Mining Principles,*[24] which applies to all members of WGC,[25] and for refining companies, it is LBMA's *Responsible Gold Guidance.*[26] In 2021, WGC member companies made a commitment to regularly report on their progress in decreasing their climate risks and environmental impact, in line with TCFD recommendations. LBMA's Responsible Sourcing programme is mandatory for every refining company with LGD certification. Adherence to the audited process demonstrates compliance with responsibility and sustainability criteria to market operators.[27]

It should be noted that the EU regulation on minerals originating from conflict-affected and high-risk areas (EU 2017/821[28]) came into force on 1 January 2021, laying down supply chain due diligence and disclosure obligations for importers of certain minerals and ores, including gold, in relation to suppliers.

It should also be noted that while mines using large-scale technologies account for the vast majority of production, it is small-scale mining that is the most prone to ESG risks. The Alliance for Responsible Mining was established to explore and mitigate these problems.[29]

[22] Gold Industry Declaration of Responsibility and Sustainability Principles (https://www.gold.org/gold-industry-declaration)
[23] Sustainable Development Goals (SDG)
[24] Responsible Gold Mining Principles (https://www.gold.org/industry-standards/responsible-gold-mining)
[25] Currently accounting for nearly 60 per cent of annual large-scale gold production.
[26] Responsible Sourcing Programme, Responsible Gold Guidance (https://www.lbma.org.uk/responsible-sourcing)
[27] Several central banks, including the Magyar Nemzeti Bank, only have gold bars with this certification.
[28] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02017R0821-20201119
[29] Alliance for Responsible Mining (https://www.responsiblemines.org/en/)

4.2. Responsible and sustainable investment opportunities

4.2.1. Certificates, attestations and trademarks

Responses to evolving consumer expectations are gradually appearing on the gold market as well, with products such as gold bars, coins and jewellery with various certifications that prove the origin and other ESG features of the gold, demonstrating to buyers that various sustainability criteria are met.

There are several such certifications: some include designation of origin and certify the point of origin of the gold, while others confirm that environmentally friendly production processes are in place. For example, the Carbon Trust Footprint Label[30] shows that the carbon footprint of the company manufacturing the product decreases every year, in line with a decarbonisation plan certified and regularly audited by the Carbon Trust, and the remaining emissions are offset according to the ISO 14067 standard.[31]

Some gold refining companies use various analytical tools to assess supply chain risks. For example, the Swiss refiner Metalor and the University of Lausanne developed the Geoforensic Passport approach that determines the origin of gold based on various chemical components (*Schütte 2023*).

The various certifications, such as credit ratings, typically incur additional costs for producers. *Gruber and Montemurro* (*2021*) examined what information market participants want to be disclosed and found that the designation of origin is extremely important: buyers are willing to pay a premium of up to 2 per cent for such certificates. There are certificates attesting compliance with more broadly interpreted ESG criteria, with a price premium of 1.7 to 10 per cent as compared to uncertified gold. These include certifications by *Fairmined,*[32] by *Fairtrade*[33] and by *Better Gold Initiative*, which cost 4,000–6,000 USD/kgAu, 2,000 USD/kgAu and 1,000 USD/kgAu, respectively (*Gruber – Montemurro 2021*). The price premium buyers are willing to pay for a "green version" of a given product depends on the supply and demand structure (*Azevedo et al. 2022*).

4.2.2. Alternative forms of investment

Baur et al. (*2020*) presented an interesting idea: the actual extraction of gold is not strictly necessary for investors to access the performance of the gold market, and thus they propose to leave gold in the ground, in its natural vault. The authors recommend investing in companies – as an alternative to investments involving

[30] https://www.carbontrust.com/en-eu/what-we-do/product-carbon-footprint-labelling/product-carbon-footprint-label
[31] International standard defining methodologies for measuring the carbon footprint of various products: https://www.iso.org/standard/71206.html
[32] https://fairmined.org/what-is-fairmined/
[33] https://www.fairtrade.org.uk/buying-fairtrade/gold/

actual mining – that identify and secure gold reserves, but do not extract them. They analyse their research question on portfolios consisting of Australian gold exploration companies, and conclude that – despite the uncertainties about the quantity and quality of gold in specific locations – this "green gold" is strongly correlated with the performance of conventional gold investments.

The study presented above is an intriguing thought experiment, but it must be noted that with this form of gold investment the benefits of investing in physical gold probably cannot be realised. These include independence from the issuer, the lack of credit risk and, most importantly, the certainty that the asset concerned can be physically stored on the territory of one's own country. The causal relationships behind the phenomena presented in the paper should also be explored further, as correlation may have a number of underlying factors.

5. Conclusion

An increasing number of central banks publish sustainability and climate risk analyses according to the recommendations of TCFD, focusing mostly on their investments in bonds and equities. Despite its significant role in central bank reserves, gold as a separate investment asset class has rarely been discussed in these reports, even though climate change can have negative socio-economic consequences that may increase the significance of safe-haven assets.

Investor demand for gold is mostly determined by strategic and financial considerations, but, taking the above aspects into account, the sustainability and climate risks of gold should also be explored. This kind of analysis is not only relevant for central banks that intend to buy gold, but also for those that hold gold reserves, as the value of their investments is determined by the price of gold on the secondary market, which, through supply and demand, may be affected by processes potentially triggered by climate change.

While best practice is emerging in existing climate risk analyses, there is still no widely accepted methodology for gold. Gold, like bonds and shares, is an investment asset, but there are significant differences between these products, which limits the comparability of their climate risks. It can be established that gold is practically indestructible: it will not be damaged even during (climate) disasters, and therefore its physical risk exposure is negligible.

In the case of gold, the focus should be on total emissions impacts instead of intensity ratios. For shares and bonds, WACI expresses continuous, annualised emissions and value added and determines the degree of transition risks from that. As opposed to this, gold bars purchased have a one-time GHG impact, and no significant emissions are involved in their holding. For the sake of comparability, it would be useful to bring the emissions indicators used for gold closer to the concept applied to securities – for this purpose, the analysis of total emissions per investment value seems suitable. Some analyses suggest that the one-time emissions of gold investments can be divided by a hypothetical holding period, which means the longer the planned investment horizon, the more favourable the indicator as compared to other investments that keep generating new emissions.

With regard to transition risks, it should be noted that potential regulatory changes or evolving consumer preferences have no direct effect on physical gold already included in investment portfolios. Nonetheless, considering that the value of existing gold investments is determined by the price shaped by prevailing market supply and demand conditions, indirect impacts may also play a role. Further research is needed to explore this.

Currently available findings in the literature and examples seen in practice suggest that there is still no consensus about reporting on the climate risks of gold investments. However, as gold investments play a significant role in central bank reserves, and environmental sustainability-related financial disclosures are more and more widespread, an increasing demand for such reporting can be expected in the future.

References

Asztalos, L.G. – Asztalos, P. (2011): *A globális aranypiac varázslatos paradoxonjai* (*The magical paradoxes of the global gold market*). Hitelintézeti Szemle, 10(2): 127–141. https://www.bankszovetseg.hu/Content/Hitelintezeti/HSz2011_2_127-141.pdf

Alimukhamedov, K. (2024): *Gold investment handbook for asset managers.* The World Bank. https://hdl.handle.net/10986/41127

Arslanalp, S. – Eichengreen, B. – Simpson-Bell, C. (2023): *Gold as International Reserves: A Barbarous Relic No More?*. Journal of International Economics, 145, 103822. https://doi.org/10.1016/j.jinteco.2023.103822

Azevedo, M. – Moore, A. – van den Heuvel, C. – Hoey, M. (2022): *Metals & Mining Practice*: *Capturing the green-premium value from sustainable materials*. McKinsey & Company. https://www.mckinsey.com/~/media/mckinsey/industries/metals%20and%20mining/our%20insights/capturing%20the%20value%20from%20sustainable%20materials/capturing-the-green-premium-value-from-sustainable-materials-vf.pdf?shouldIndex=false

Banai, Á. – Kolozsi, P.P. – Ladányi, S. (2021a): *The Role of Gold in the Digital Age*. Financial and Economic Review, 20(3): 138–146. https://hitelintezetiszemle.mnb.hu/en/fer-20-3-a2-banai-kolozsi-ladanyi

Banai, Á. – Kolozsi, P.P. – Veres, I. (2021b): *Biztonság és bizalom: az arany mint Magyarország nemzetközi tartalékainak stratégiai eleme* (*Security and trust: gold as a strategic element of Hungary's international reserves*). Feature article, Magyar Nemzeti Bank. https://www.mnb.hu/letoltes/banai-adam-kolozsi-pal-peter-veres-istvan-az-arany-mint-a-nemzetkozi-tartalekok-strategiai-eleme.pdf

Bánfi, T. (2022a): *Az aranypénzrendszer működése* (*The operation of the gold standard*). https://banfitamas.hu/2022/10/26/az-aranypenzrendszer-mukodese1/

Bánfi, T. (2022b): *Az arany demonetizálódásáról* (*On the demonetization of gold*). https://banfitamas.hu/2022/10/26/az-arany-demonetizalodasarol1/

Bánfi, T. – Hagelmayer, I. (1989): *Pénzelmélet és pénzügypolitika* (*Monetary theory and monetary policy*). Közgazdasági és Jogi Könyvkiadó, Budapest.

Baur, D.G. – Oll, J. (2017): *The Role of Gold and the VIX in Investment Portfolios – A Financial and Sustainability Perspective*. SSRN. http://dx.doi.org/10.2139/ssrn.3069283

Baur, D.G. – Smales, L.A. (2018): *Gold and Geopolitical Risk*. SSRN. http://doi.org/10.2139/ssrn.3109136

Baur, D.G. – Smales, L.A. (2020): *Hedging Geopolitical Risk with Precious Metals*. Journal of Banking and Finance, 117, 105823. https://doi.org/10.1016/j.jbankfin.2020.105823

Baur, D.G. – Trench, A. – Ulrich, S. (2020): *Green gold. A Gold Mining Perspective.* SSRN. http://dx.doi.org/10.2139/ssrn.3512681

Beckman, J. – Czudaj, R. (2012): *Gold as an Inflation Hedge in a Time-Varying Coefficient Framework*. Ruhr Economic Paper No. 362. http://dx.doi.org/10.2139/ssrn.2144781

Bouoiyour, J. – Selmi, R. – Wohar, M.E (2018): *Measuring the response of gold prices to uncertainty: An analysis beyond the mean*. Economic Modelling, 75(November): 105–116. https://doi.org/10.1016/j.econmod.2018.06.010

Bundesbank (2024): *Climate-related disclosures by the Deutsche Bundesbank 2024*. https://www.bundesbank.de/resource/blob/844900/7d5fc06ce856b79af8fc6176e4edf079/mL/2024-klimabericht-data.pdf

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(April): 143–150. https://doi.org/10.1016/j.jclepro.2018.01.114

Conlon, T. – Lucey, B.M. – Uddin, G.S. (2018): *Is Gold a Hedge Against Inflation? A Wavelet Time-Scale Perspective*. Review of Quantitative Finance and Accounting, 51: 317–345. https://doi.org/10.1007/s11156-017-0672-7

ECB (2019): *As market matures central banks conclude that a formal gold agreement is no longer necessary*. Press Release, ECB. https://www.ecb.europa.eu/press/pr/date/2019/html/ecb.pr190726_1~3eaf64db9d.en.html

Fazekasné Szikra, Á. – Pivarcsi, Á. (2017): *Az aranypiac rövid áttekintése* (*A brief overview of the gold market*). MNB Oktatási füzetek 18. https://www.mnb.hu/letoltes/oktatasi-fuzetek-18-szam-2017-oktober-fazekasne-szikra-agnes-pivarcsi-agnes-az-aranypiac-rovid-attekintese.pdf

Greenhouse Gas Protocol (2011): *Corporate Value Chain (Scope 3) Accounting and Reporting Standard – Supplement to the GHG Protocol Corporate Accounting and Reporting Standard*. https://ghgprotocol.org/corporate-value-chain-scope-3-standard

Gosh, D. – Levin, E.J. – Macmillan, P. – Wright, R.E. (2001): *Gold as an inflation hedge?*. Studies in Economics and Finance, 22(1): 1–25. https://doi.org/10.1108/eb043380

Gruber, P.H. – Montemurro, P. (2021): *Paying for ESG: The Provenance Premium for Precious Metals.* Università della Svizzera Italiana. https://people.lu.usi.ch/gruberp/files/gruber_2021_paying_for_esg_gold.pdf

Hagelmayer, I. – Boros, I. – Bánfi, T. (1975): *Az aranydeviza-rendszer kudarcai és tanulságai* (*The Failures and Lessons of the Gold Standard System*). Közgazdasági és Jogi Könyvkiadó, Budapest.

Haque, N. – Norgate, T. (2014): *The greenhouse gas footprint of in-situ leaching of uranium, gold and copper in Australia.* Journal of Cleaner Production, 84(December): 382–390. https://doi.org/10.1016/j.jclepro.2013.09.033

Kolozsi, P.P. – Ladányi, S. – Straubinger, A. (2022): *Measuring the Climate Risk Exposure of Financial Assets – Methodological Challenges and Central Bank Practices*. Financial and Economic Review, 21(1): 113–140. https://doi.org/10.33893/FER.21.1.113

Ladányi, S. – Paulik, É. (2018): *Egy új aranykor kezdete? – Hazatért a tízszeresére növelt magyar aranytartalék* (*The beginning of a new golden age? – Increased tenfold, Hungarian gold reserves have returned home*). Feature article, Magyar Nemzeti Bank. https://www.mnb.hu/kiadvanyok/szakmai-cikkek/befektetesek-megtakaritasok/ladanyi-sandor-paulik-eva-egy-uj-aranykor-kezdete-hazatert-a-tizszeresere-novelt-magyar-aranytartalek

Li, J. – Wang, Y. – Song, Y. – Su, C. W (2023): *How resistant is gold to stress? New evidence from global supply chain.* Resources Policy, 85(Part B), 103960. https://doi.org/10.1016/j.resourpol.2023.103960

Lucey, B. – Tully, E. – Poti, V. (2003): *International Portfolio Formation. Skewness and the Role of Gold.* SSRN. http://dx.doi.org/10.2139/ssrn.452482

Lőrincné Istvánffy, H. (2004): *Nemzetközi Pénzügyek* (*International Finance*). Aula Kiadó, Budapest.

MNB (2023): *The Magyar Nemzeti Bank's Charter of Sustainable and Responsible Investment*. Magyar Nemzeti Bank. https://www.mnb.hu/letoltes/the-magyar-nemzeti-bank-s-charter-of-sustainable-and-responsible-investment.pdf

MNB (2024): *The Magyar Nemzeti Bank's Climate-Related Financial Disclosure*. Magyar Nemzeti Bank. https://www.mnb.hu/en/publications/reports/the-magyar-nemzeti-bank-s-climate-related-financial-disclosure

Marczis, D. – Karácsony, T. (2024): M*érés nélkül nincs zöld fordulat – Helyezzük kontextusba a karbonintenzitási mutatót!* (*No green transition without measurement – Putting carbon intensity indicators into perspective*). Blog entry, MNB Intézet. https://mnbintezet.hu/meres-nelkul-nincs-zold-fordulat-helyezzuk-kontextusba-a-karbonintenzitasi-mutatot/

Mudd, M.G. (2007): *Global trends in gold mining: Towards quantifying environmental and resource sustainability.* Resources Policy, 32(1–2): 42–56. https://doi.org/10.1016/j.resourpol.2007.05.002

NGFS (2024): *NGFS long-term scenarios for central banks and supervisors*. Network for Greening the Financial System. https://www.ngfs.net/en/ngfs-climate-scenarios-phase-v-2024

Norgate, T. – Haque, N. (2012): *Using life cycle assessment to evaluate some environmental impacts of gold production*. Journal of Cleaner Production, 29–30(July): 53–63. https://doi.org/10.1016/j.jclepro.2012.01.042

Nuss, P. – Eckelman, J.M. (2014): *Life Cycle Assessment of Metals: A Scientific Synthesis*. PLoS ONE, 9(7), e101298. https://doi.org/10.1371/journal.pone.0101298

Palotai, D. – Veres, I. (2020): *Mérlegen az aranytartalék: A stabilitás növelése mellett kézzelfogható hasznot is hozhat a nemesfém* (*The gold reserve on the scale: In addition to increasing stability, the precious metal can also bring tangible benefits*). Feature article, Magyar Nemzeti Bank. https://www.mnb.hu/kiadvanyok/szakmai-cikkek/devizatartalek-es-serulekenyseg/palotai-daniel-veres-istvan-merlegen-az-aranytartalek-a-stabilitas-novelese-mellett-kezzelfoghato-hasznot-is-hozhat-a-nemesfem

Schütte, P. (2023): *Gold Sustainability Information*. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover. https://www.bgr.bund.de/EN/Gemeinsames/Produkte/Downloads/Informationen_Nachhaltigkeit/Gold_en.pdf?__blob=publicationFile&v=5

Ulrich, S. – Trench, A. – Hagemann, S. (2020): *Greenhouse gas emissions and production cost footprints in Australian gold mines*. Journal of Cleaner Production, 267, 122118. https://doi.org/10.1016/j.jclepro.2020.122118

Ulrich, S. – Trench, A. – Hagemann, S. (2022): *Gold mining greenhouse gas emissions, abatement measures, and the impact of a carbon price*. Journal of Cleaner Production, 340, 130851. https://doi.org/10.1016/j.jclepro.2022.130851

Veres, I.A. (2024): *Az arany reneszánsza* (*The Renaissance of Gold*). Feature article, Magyar Nemzeti Bank. https://www.mnb.hu/letoltes/mnb-szakmai-cikk-veres-istvan-az-arany-reneszansza.pdf

WGC (2018): *Gold and Climate Change: An introduction.* World Gold Council. https://www.gold.org/download/file/8306/gold-and-climate-change-report.pdf

WGC (2019a): *Gold and Climate Change: Current and future impacts.* World Gold Council. https://www.gold.org/goldhub/research/gold-and-climate-change-current-and-future-impacts

WGC (2019b): *Responsible Gold Mining Principles.* World Gold Council. https://www.gold.org/industry-standards/responsible-gold-mining

WGC (2020): *Gold and Climate Change: The energy transition.* World Gold Council. https://www.gold.org/download/file/15455/Gold-and-Climate-Change-The-Energy-Transition.pdf

WGC (2021a): *Gold and Climate Change: Decarbonising investment portfolios.* World Gold Council. https://www.gold.org/download/file/16407/Gold-and-Climate-Change-decarbonising-investment-portfolios.pdf

WGC (2021b): *The Social and Economic Contribution of Gold Mining.* World Gold Council. https://www.gold.org/esg/the-social-and-economic-contribution-of-gold-mining