Global trends in gold mining: Towards quantifying environmental and resource sustainability?

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Abstract

In recent years, due to public concern over perceived and actual environmental impacts, the global mining industry has been moving towards a more sustainable framework. For gold mining, there are a number of fundamental issues with regard to assessing sustainability. Commonly perceived as a finite and non-renewable resource, long-term gold production trends include declining ore grades and increasing solid wastes (tailings, waste rock) and open cut mining. Conversely, core sustainability issues include water, energy and chemical consumption and pollutant emissions—also known as ‘resource intensity’. It is important to recognise the links between gold production trends and resource intensity, as this is critical for understanding future sustainability challenges. This paper links data sets on historic gold mining production trends with emerging sustainability reporting to estimate resource intensity, demonstrating the sensitivity of ore grade for gold production and sustainability. Final judgement of the sustainability of gold mining must take account of the sensitivity of the ore grade in the resource intensity of gold production. This has implications for environmental policy and sustainability reporting in the gold mining sector.

JEL classification: Q56; Q32; L72

Keywords: Gold mining; Resource intensity; Sustainable mining; Ore grade; Waste rock

Introduction

The mining and production of gold is indeed an ancient human tradition and presently occurs all over the world (Buttermann and Amey, 2005). The history of gold mining is commonly associated with both positive and negative social, political, economic and environmental impacts (e.g. Ali, 2006; Corte and Coulston, 1998; Muezzinoglu, 2003). In recognition of these impacts, the industry has in recent years been moving towards a more sustainable framework. An important development has been the adoption of recommendations in ‘Minerals Mining and Sustainable Development’ report (IIED and WBCSD, 2002), presented by the global mining industry at the Johannesburg Earth Summit in 2002. Many mining companies have begun to report on their sustainability performance alongside their financial performance, based on company standards or external guidelines such as the recently developed Global Reporting Initiative (GRI, 2006). The application of sustainable development concepts to mining remains problematic, however, especially in the gold sector of the global mining industry.

This paper compiles and analyses available sustainability data on gold mining for Australia, North America, Africa and the Asia-Pacific, including waste volumes, ore grades, economic resources and resource intensity. The paper presents a fundamental analysis of a major policy area—that of environmental and resource sustainability—which currently affects gold mining. It also provides a critical basis to underpin further policy debate through real data for life-cycle and sustainability assessments. Formal consideration of the social aspects of sustainability related to gold mining is beyond the scope of this paper.

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Sustainable development concepts for mining

The observation that mining has both positive and negative impacts is not new—with significant treatises dating back to Agricola (1556) and earlier. Following the near-continual global mining boom since about 1960, there has been a wide-ranging debate about the sustainability of modern mining. This section presents a broad review of this discussion with a summary relevant for gold mining in the context of this paper.

The most common starting point for discussing sustainability is the definition proposed by the 1987 World Commission on Environment and Development (WCED, or the ‘Brundtland Commission’), namely ‘to meet the needs of the present without compromising the ability of future generations to meet their needs’ (WCED, 1990).

Although this is a somewhat open definition (Hilson and Basu, 2003), in the context of mining, this is generally taken to include the availability of resources and a productive environment and healthy community at both current and former mining sites (e.g. Azapagic, 2004; Cowell et al., 1999; Gordon et al., 2006; Yua et al., 2005).

The mining of a perceived ‘finite’ resource (i.e. mineral resources are non-renewable) has been commonly argued as intrinsically unsustainable, thereby reducing the ability of future generations to supply that particular mineral. The most cited study for this position is perhaps the 1972 Club of Rome analysis ‘Limits to Growth’ (Meadows et al., 1972), with numerous studies, reports and papers also continuing the perceived non-renewable nature of mineral resources (e.g. Bartlett, 2006; Whitmore, 2006; Young, 1992). Other commentators, including some from the mining industry, have argued in response that economic mineral resources are not a stationary, solitary figure, but rather a function of prevailing economic, social and environmental constraints (e.g. Hancock, 1993; Horé-Lacy, 1986; IED & WBCSD, 2002; Tilton, 1996, 2003; Trubetskoi et al., 2002; Yua et al., 2005; Eggert, 2006).

Despite the perception that mineral resources are finite, there have been few systematic quantitative analyses of known mineral resources that assess the factors affecting known economic mineral resources and their potential extraction. There are selected data available in national mining industry periodicals (e.g. Geoscience Australia, var.; Natural Resources Canada, var.; US Bureau of Mines, var.; United States Geological Survey, var.a). However, these are not complete, as they do not present data for ore tonnage, ore grade, contained metal and associated waste rock. For gold, Craig and Rimoldt (1998) have provided a brief analysis of economic resources for the world and the United States, although their study does not include data on waste rock and tailings (ore) from mining or the ore grade of economic gold resources.

It is important to understand the nature of mineral resources, since issues such as ore grades, impurities (e.g. arsenic, mercury), waste rock, geological and mining constraints, technological requirements as well environmental issues such as water, chemicals, energy and pollutants and socio-economic constraints are all critical in determining whether a quantified mineral deposit is an extractable, valuable resource. In Australia, this recognition of the broader context of ‘economic’ mineral resources is embedded into the Joint Ore Reserves Code (JORC) code for reporting economic mineral resources (AusIMM et al., 2004; Stephenson, 2001).

The issue of ‘non-renewable’ mineral resources is critical in the sustainability debate as it relates to present generations meeting their needs for metals and minerals while still allowing for future generations to provide for their anticipated requirements (Cowell et al., 1999).

A major challenge in this regard is the evolving environmental and social costs of extracting mineral resources—especially, when compared to the equivalent costs from secondary sources and processes. This begs the question of whether future mining will cost more than at present.

The environmental and social health of a region and community as affected by mining—positively or negatively—remains a contentious area for the sustainability debate and the mining industry (Hancock, 1993), particularly for the developing world (e.g. Ali, 2006; Kumah, 2006).

Historically, the mining industry has caused significant environmental impacts through poor waste management, lack of or poor rehabilitation, an emphasis on production over environmental impacts, and so on. This in turn is closely related to social impacts and challenges of varying degrees of difficulty. Agricola (1556), a strong supporter of mining and its contribution to society, documented this dilemma eloquently in a regional and local context more than 450 years ago.

The context for sustainable development for mining is still essentially the same—balancing the potential environmental and social risks with the economic risks. The primary difference is now that the issue is of a truly global scale and concern rather than Agricola’s locale of central Europe. For gold mining in particular, some continue to argue that there is net detriment or no net benefit from gold mining (see Ali, 2006; Whitmore, 2006).

Since about the 1970s onwards in most countries (especially developed nations with advanced mining industries), new and existing mining projects have been required to meet an array of environmental requirements set by legislation, policy and statutory authorities which emerged during this decade (e.g. an Environmental Protection Agency or EPA). The mining industry accepted the legitimacy of this changed landscape and worked to improve industry standards and performance throughout the 1970s–1980s, primarily to meet legal requirements but also to ensure social acceptance of existing and future mines (Hancock, 1993; Horé-Lacy, 1986; Mulligan, 1996).

The 1992 Rio Earth Summit focussed global attention on sustainability, with public sentiment beginning to accept
the legitimacy of the need for sustainable development and combined social, economic and environmental performance (McAllister et al., 1999). Surprisingly, only a handful of mining companies were pro-active in responding to this paradigm shift.

WMC Resources released an Australian mining company’s first ‘Environmental Progress’ report in 1995. As an annual report of major prominence alongside its financial reports, these incorporated social and community issues in 2000 and were subsequently expanded further and renamed ‘Sustainability’ in 2001 (see WMC, var.).¹ In Canada, companies such as Placer Dome followed a similar path, releasing the first Sustainability report for their Asia-Pacific operations in 1997, followed by an annual global operations Sustainability report from 1998 (Placer Dome, var.). Both WMC, Placer Dome and other companies relied on policies, performance measures and reporting procedures developed internally—though broadly within the sustainability framework of economic, social and environmental performance. Over the past decade, there has been a rapid increase in the publication of environmental or sustainability reports (or notable sections in existing annual reports) by mining companies, which outline their social, economic and environmental performance either qualitatively or quantitatively or both (Byrne et al., 2002; van Berkel and Bossilkov, 2004).

In the build-up towards the 2002 Johannesburg Earth Summit (the ‘Rio + 10’ follow-up), the global mining industry established a broad process to examine mining, sustainability and the performance of the industry. The study, which was called the ‘Mining, Minerals and Sustainable Development’ (MMSD) project (IIED & WBCSD, 2002), was formally launched at Johannesburg. The numerous MMSD reports included a principal report and various regional reports and associated studies.

The MMSD project articulated a pivotal change in approaching sustainability with a move away from arguing individual mines may be sustainable, to the sector as a whole contributing to sustainable development (IIED & WBCSD, 2002). This distinction is of fundamental and critical importance. The revised emphasis on ‘contributing to sustainable development’ allows broader consideration of a balance of social, economic and environmental facets for the industry as whole. Thus, it is the sum of all individual mines over time and space and their respective resources, impacts and benefits, which should be considered in ascribing sustainability to mining. While individual mine performance remains critical, a focus on the sector as a whole is necessary to assess sustainability in a proper way (Hilson, 2001).

Since about 1995, an increasing amount of research has suggested sustainable development indicators relevant for mining industry reporting (see Azapagic, 2004; Byrne et al., 2002; Hilson and Basu, 2003; van Berkel and Bossilkov, 2004). These studies examine indicators such as jobs, water usage, pollutant emissions, solid wastes, rehabilitation and land use, energy source and consumption, and health and safety. They provide a broader set of indicators than those developed by companies such as WMC and Placer Dome. These derived from the various principles for sustainability, including the precautionary principle, inter- and intra-generational equity, biodiversity, pollution minimisation and maintenance of capital.

A broader initiative for sustainability reporting and indicators is that of the Global Reporting Initiative (GRI)—a coalition of the United Nations, industry, government and civil society groups. Established in 1997, the GRI released a draft reporting protocol in 1999, launching the first edition in 2000 and the third edition in October 2006 (GRI, 2006). The GRI aims to achieve uniform and consistent reporting on sustainability performance, allowing this to be as routine and comparable as financial reporting. Increasing numbers of mining companies now report sustainability performance based on its protocol. A specific mining sector supplement, released in pilot form in 2005, facilitates improved and more relevant sustainability reporting (GRI, 2005).

A principal benefit of the emerging regime is the increasing abundance of data available to assess the resources required for new mineral production. This allows estimation of water, energy, chemicals requirements as well as resultant wastes and pollutant emissions (e.g. tailings, waste rock, carbon dioxide). This is termed ‘resource intensity’ for the purposes of this paper (also known as eco-efficiency; van Berkel, 2007). Access to these data is critical for cleaner production and wholistic life-cycle analyses, both of which are foundation tools for sustainability assessments (e.g. Guerin, 2006; Norgate and Rankin, 2002; Stewart and Petrie, 2006). For minerals and metal mining (particularly gold mining), this is a difficult challenge and gaps remain to facilitate more informed assessment (Stewart et al., 2004; Stewart and Petrie, 2006).

Predicting sustainability challenges associated with gold mining also requires knowledge of historical production trends as well as the relationship between mineral production and resource intensity. As an example, one key production trend which is reasonably well understood is that of declining gold ore grades (e.g. Craig and Rimstidt, 1998; Müezzinoglu, 2003). Despite the global scale and reach of the modern mining industry, especially gold mining, understanding of the links between production and resource intensity is still limited, though it appears to be improving.

Increasing availability of relevant data affords the opportunity to quantify resource intensity for gold mining and to link it to production performance reporting. These relationships can then be used in the sustainability debate, which surrounds gold mining. The remainder of this paper compiles and analyses these data sets for global gold mining.

¹WMC was taken over by BHP Billiton Ltd. in 2005.
Data sources

The various aspects of sustainability investigated in this paper are assessed through the compilation of detailed data on

- gold ore grade, production and waste volumes—government series/periodicals on mining, recent company annual reports;
- energy, water and cyanide consumption and greenhouse emissions (as carbon dioxide equivalents, CO$_2$-e)—recent company annual environmental/sustainability reports; and
- economic gold ore resources—government series/periodicals on mining, technical literature.

These aspects are of prime importance in understanding environmental and resource sustainability (Dow and Minns, 2004).

It is possible to obtain historical information on gold production, prices and ore grades using the following data sets:

- World gold production and price (US$)—1851–2005 (ABARE, var.; Govett and Harrowell, 1982; Kelly et al., 2004);
- United States ore grade and production—1907–1993 (Craig and Rimstidt, 1998);
- South African ore grade and production—1893–2005 (Chamber of Mines South Africa, 2006);
- Australian ore grade and production—1859–2005 (Mudd, 2007);
- Canadian ore grade and production—1945–2004 (with some gaps) (Natural Resources Canada, var.);

Less data are available on waste rock quantities for gold mining. Natural Resources Canada (var.) reports information for Canada for both underground and open cut mines from 1980 to 2004. For Australia, Mudd (2007) has collated data for individual mines to obtain a total estimate of waste rock. Yet, many gold mines do not report these data and so such estimates are incomplete. Data for other countries are also based on individual mines taken from company annual reports. It is presented as ratios of waste rock to ore (tonnes waste rock/tonnes ore) as well as waste rock totals per country—despite these totals for most countries being incomplete.

A list of the companies used to compile data on resource intensity appears in Table 1. All references are to the respective company social/environmental or sustainability reports. While it includes most major gold companies, it does not capture all companies who report sustainability performance. The companies listed represent a significant portion of world gold production, and a broad geographic spread of mines in Africa, North, Central and South America, Australia and the Asia-Pacific. If energy data was presented as fossil fuels only, this was converted to energy and greenhouse emissions using Australian Greenhouse Office (2005). In general, an increasing degree of relevant sustainability data is being reported by mining companies over time (with access facilitated through online resources and archives). It is assumed that all sustainability data reported is of high quality and therefore comparable.

Resource intensity is presented as unit consumption per gold production (e.g. kL/kg Au, GJ/kg Au) with respect to ore grade (g/t Au) as well as with unit consumption per tonne of ore milled (e.g. kL/t ore, GJ/t ore) with respect to mill throughput (Mt ore/year). Greenhouse emissions are also presented in this fashion (e.g. t CO$_2$-e/t ore, t CO$_2$-e/ kg Au). In this way, the effects of both mine scale and ore grade can be observed.

There are data available on economic gold resources for many countries, although only data for countries such as Australia, Canada, South Africa and the United States are presented to correspond to the ore grade data included in this paper (these countries are also major global producers). ‘Resources’ is the term used broadly, especially environmental resources such as water. However, all data for economic gold ‘resources’ are reported economic reserves only—not ‘economic resources’ or ‘reserve base’ (see Geoscience Australia, var.; US Geological Survey, var.a). Although there are some differences between the methodologies for economic classification of mineral resources between countries, the specific economic reserves data presented are broadly comparable to assess relative trends over time. The ratio of resources to production is
also calculated and presented. The sources used for economic gold resources are:
- Australia: 1955 (British Commonwealth Global Liaison Office, 1956), 1960 (McLeod, 1998), 1975–2005 (Geoscience Australia, var.); and

The compiled data allow the comparison of various drivers of sustainability in gold mining, including changes in the gold price, new discoveries, new technology, social disturbances (e.g. wars), as well as the way that water, energy and reagent consumption and pollutant emissions relate to these.

Results

Details of world gold production over the past 150 years appear in Fig. 1. The details of gold ore grades for hard rock mining for the United States, Australia, South Africa, Brazil and Canada are shown in Fig. 2. The prices of gold in both dollars of the day and 1998 US dollars are also plotted in Fig. 2. The effects of the California gold rush in 1849, followed by the gold rushes in Australia in 1851 and South Africa in 1884 are evident. The development of new cyanide milling technology (carbon-in-pulp) and the major rise in the real price of gold in the 1970s led to expanded production from 1980 onwards.

The supply and consumption of economic energy is often a key factor in the viability of gold mines, with diesel being particularly important, though natural gas use is increasing. The available data for energy consumption are shown in Fig. 3, including a preliminary power regression of all data points. Data over time are reported in Table 2.

The availability of a suitable water supply is important for any mine, though water quality for gold mining is no longer as critical since the development of carbon-in-pulp technology. This process can efficiently utilise hypersaline waters (e.g. at many gold mines in Western Australia; see McCowan and White, 1993; Norgate and Lovel, 2006; Sparrow and Woodcock, 1993). As there is no consistency in reporting waters of various sources or quality, the data are presented as total water consumption. There is presently little reporting of whether water comes from either fresh or recycled sources, or about various levels of water quality or salinity. The available data for water consumption between 1991 and 2006 is shown in Fig. 4, including a preliminary power regression of all data points; averages are reported in Table 2.

Using cyanide in gold mining poses environmental risks that need to be pro-actively managed (Logsdon et al., 1999; Muezzinoğlu, 2003; Stenson, 2006). Several tailings dam failures and cyanide transport accidents since 1995 have led to increased public scrutiny (Kumah, 2006), although at present there remains no effective alternative (Hilson and Monhemius, 2006; Muir and Aylmore, 2004). Many companies now publish sustainability reports, which give details of water and energy data but few also include cyanide use. The ‘International Cyanide Management
Fig. 2. Average gold ore grade: the United States, Australia, South Africa, Brazil and Canada and gold price in dollars of the day and US$1998 real price.
Code’ (ICMI, 2002) as well as the more recent Global Reporting Initiative Mining Supplement (GRI, 2005) are voluntary and do not require compulsory reporting of cyanide consumption. The available data for cyanide consumption between 1992 and 2006 appear in Fig. 5, which also include a preliminary power regression of all data points; average data are summarised in Table 2.

Greenhouse emissions, primarily through fossil fuels use, provide an environmental challenge for the mining industry globally but this is particularly difficult for gold mining that involves large-scale open cut operations (Dow and Minns, 2004). As with water and energy, greenhouse emissions are presented as unit release per gold production with respect to ore grade as well as unit release per tonne of ore milled with respect to mill throughput, data between 1991 and 2006 are shown in Fig. 6; average data appear in Table 2.

The extent of economic gold resources is known for some countries over time. In general only total metal is presented, with ore grade rarely presented with total metal resources. The British Commonwealth Geological Liaison Office (1956) published data for major gold-producing countries such as Canada, Australia and South Africa as
Table 2

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<th>Greenhouse emissions (t CO₂-e/kg Au)</th>
<th>Energy consumption (GJ/kg Au)</th>
<th>Cyanide consumption (kg CN/kg Au)</th>
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well as several other minor producing countries. The estimated gold ore grade for Canada, Australia and South Africa was about 7.15, 2.65 and 9.83 g/t Au, respectively (including gold and base metal ores). For Australia, Woodall (1990) estimated a gold ore grade of 1.85 g/t Au, including gold and base metal ores, totalling 1644 t Au. A more recent estimate suggests a resource ore grade of about 1.1 g/t Au totalling 9277 t Au (based on data compiled by the author; see Mudd, 2007). The data for economic resources and the ratio of production to resources are shown in Fig. 8.

Discussion

This paper compiles and presents data on critical aspects of global gold mining, possibly for the first time. A number of significant issues emerge from this with respect to its policy implications for the environmental and resource sustainability of the sector.

Gold mining production

The gold mining boom since the late 1970s has been facilitated by the combination of a real price rise, the development of carbon-in-pulp (‘CIP’) milling technology, and to a lesser extent the evolution in large-scale bulk earth-moving vehicles and mining techniques.

These factors led to more exploration, focused initially on previous gold producing provinces, along with the development of many new gold mines around the world. These mines have often been based on open cut mining techniques, which allow more complete extraction and processing of all gold-mineralised ore. The economics of gold mining were radically re-defined during this period. It led to an extra-ordinary renaissance in some countries such...
as Australia (e.g. Close, 2002), the United States (Craig and Rimstidt, 1998) and Canada for about 20 years. In South Africa, by contrast, this pattern did not emerge, due to the deep underground nature of their gold mines as well as political and social issues.

From a global view, based on gold resources data presented, there is only sufficient known economic resources to sustain existing levels of newly mined production for less than 20 years. The future extent of economic resources and production is, of course, difficult to predict but will continue to depend on exploration effort, economics, social and environmental issues, technology as well as the recycling of the world gold stockpile.

**Gold ore grade**

There is a clear trend of declining ore grades in the countries reviewed, namely Brazil, Australia, South Africa, Canada and the United States. Although there is no similar data set for the ore grade of the world’s economic resources, the decline in the grade of ore milled seems a reasonable reflection of the decline in the ore grade of economic resources (comparing previous ore grade data for resources with Fig. 2). Furthermore, the ore grades of most data sets relate to yield or extraction only and do not reflect the true assay of mined gold ore. In Australia, ore grade is only based on true assay data from about 1980 onwards with generally all data prior to this being yield only (Mudd, 2007). It is therefore not possible to assess the true efficiency of gold extraction over an extended period.

Over the past 150 years, the remaining tailings from gold mining are often easily re-processed to extract further gold as economics and technology evolve. True ore grades in the 1800s and early 1900s are therefore likely to be considerably higher than the data presented, giving a true decline of ore grades, which is more rapid than that shown. The pace of future decline in average ore grade is difficult to predict but, based on existing operating mines and undeveloped resources reported by numerous companies, it is likely to continue to gradually decline, though perhaps at a slightly slower pace than recent history.

**Water consumption**

For water consumption, there is considerable scatter in both graphs in Fig. 4 (per gold grade and per ore milled). This seems attributable to the varying complexity of gold mines, such as local climate and water resources, metallurgical differences between ores, the type and degree of processing (e.g. gold produced as bullion or in an ore concentrate, also heap leaching), the number of active mines supported and their configuration (underground, open cut). Adding to this complexity are issues of water quality and the degree of water recycling (some companies only report new or imported water used and do not account for recycled water). Although modern gold mining is a relatively well-understood industrial enterprise, the demands for water vary according to site-specific issues.

Despite this complex variability between mines, the data in both graphs in Fig. 4 do suggest overall relationships (as shown by their respective power regressions). Firstly, higher grade gold mines (>6 g/t Au) typically have a very low water cost per gold produced while lower grade mines (<2 g/t Au) generally have a somewhat higher water cost per gold produced. Gold mines with a high throughput are commonly low-grade projects, and water use efficiency per tonne of ore milled is most likely due to economies of scale. The total quantity of water consumed, however, may still be very significant locally. There appear to be no noticeable trends with respect to time (see Table 2). Based on the combined average of all available
data, gold mining typically requires about 1.42 kL/t ore or about 691 kL/kg Au.

**Energy consumption**

Energy consumption shows a slightly lower degree of scatter in both graphs in Fig. 3 compared to water, with the same general trends also apparent in each graph’s power regression. High-grade mines use less energy per unit of gold produced while high throughputs require less energy per tonne of ore milled. Site-specific differences in energy sources between the gold mines analysed in this data set, such as natural gas, are the likely cause of the low correlations. No real trends are apparent with respect to time in Table 2. Based on the combined average of all available data, gold mining typically requires about 0.31 GJ/t ore or about 143 GJ/kg of gold produced.

**Cyanide consumption**

The extent of cyanide required to produce gold shows a closer relationship to ore grade (Fig. 5), with a coefficient of determination of 56.5%. The sensitivity of cyanide consumption per unit of gold produced relative to ore grade is clear—despite a mix of process plant types, heap leaching and different water qualities. For relatively high-grade mines (> 6 g/t Au), the cyanide cost is commonly less than 100 kg CN/kg Au, while for lower grade mines (< 2 g/t Au), the cyanide cost increases rapidly as grade declines, possibly reaching up to 1000 kg CN/kg Au or more. The average ore grade in 1993 in the USA was ~1.14 g/t while in 2005 in Australia and South Africa it was ~1.94 and ~4.7 g/t, respectively. These average country grades are visible in their relative position in Fig. 5. Cyanide consumption seems more likely to increase...
gradually in the medium term, pointing to the need for greater transparency and focus on cyanide management.

As noted previously, reporting of cyanide consumption is not compulsory according to current reporting conventions or codes. For example, the first gold mine certified under the International Cyanide Management Code, the Marigold mine in Nevada, USA, is majority controlled by a company which does not report cyanide consumption at their numerous mine sites. The quoted data for Marigold in this paper was reported by the minority owner. To improve transparency in the gold mining sector and demonstrate continuing evolution in sustainability performance, there is a strong case for reporting of cyanide.

Greenhouse gas emissions

The release of greenhouse gas emissions is a major global challenge (IPCC, 2007). The extensive use of fossil fuels in gold mining, most commonly diesel, leads to significant greenhouse emissions. As with cyanide and energy, there is a reasonable correlation between unit greenhouse emissions per unit of gold produced and ore grade as well as unit emissions per tonne of ore milled (see Fig. 6). The point at which unit emissions increase rapidly is around 5 g/t of gold. It is unfortunate that a number of major gold mines and companies do not report greenhouse emissions in their sustainability reporting. Based on the combined average of all available data, gold mining typically releases about 21.7 kg CO$_2$e/t ore or about 11.5 t CO$_2$e/kg Au. Although the high mass ratio of CO$_2$e to gold is due to the relatively small mass of gold produced, the primary function of gold for jewellery leads to major ethical and social issues in terms of accounting for the greenhouse costs.

Waste rock

The lack of attention to waste rock in sustainability reporting is also a major gap. Many mine sites globally have left a significant adverse legacy of environmental
pollution due to acid mine drainage leaching from waste rock dumps and piles. Due to this historic legacy significant regulatory and community attention has recently focussed on waste rock management, with increasing scrutiny from exploration through to planning, operations, rehabilitation and mine closure. The quantity of waste rock being mined is at least three times the amount of ore milled in Australia (Mudd, 2007), about 1.5 times in Canada for both underground and open cut mines (Natural Resources Canada, var.), and is also at least three times the amount of ore milled in the United States (see Fig. 7).

The understanding of various engineering approaches to waste rock rehabilitation to minimise acid mine drainage has evolved rapidly over the past two decades, but questions remain over their long-term performance. As shown in Fig. 7, waste rock-to-ore ratios are now commonly reaching between 2 and 10. When aggregate country totals are examined, the scale of waste rock being excavated and managed at present mines is much higher than previous gold mining, reinforcing the need to report on waste rock from gold mining to allow accurate assessments of long-term environmental risk (especially for life-cycle analysis). The lack of reporting of waste rock data suggests that the waste rock-acid mine drainage-environmental legacy link is not being broadly made within the gold mining sector. This situation needs to change dramatically if key aspects of sustainability are to be better quantified and managed.

**Economic gold resources**

As gold production has increased, many producing countries have increased their reserves and resources and consequently their resources-production ratio. Yet, the US and world resources-production ratio has gradually declined as production has increased since 1980. In 2002, South African resources dropped dramatically following re-assessments (US Geological Survey, var.-a). Overall, the resources data presented lend more weight to the industry view that economic mineral resources are a function of exploration, markets, technology and other factors, rather than supporting the ‘finite/non-renewable’ view. The future pattern of economic resources and the resources–production ratio is difficult to predict. It will depend on continued exploration, operational performance, production levels, economics and market issues, technological innovation, environmental and social issues.

**Conclusion**

This paper has compiled and presented broad-ranging data on gold mining and production, with a principal focus on the key aspects of mineral resource sustainability and environmental impacts associated with mining. This includes energy, water and cyanide consumption, waste rock volumes and greenhouse gas (carbon dioxide) emissions relative to ore grade and ore throughput. There has been a long-term decline in gold ore grades with this principally linked to evolving prices, technology and gold ore resources. The resource intensity of gold production, based on a comprehensive data set of global gold mining, shows generally stable or declining levels of resource consumption of water, energy and cyanide and reduced greenhouse emissions. As ore grades decline, unit resource cost or release increases. In terms of sustainability, given the long-term decline in ore grades, this points to the
resource intensity of gold production beginning to increase substantively in the near future—an aspect of the sustainability of mining which has to be taken more explicitly into account. These findings about the sustainability of gold mining have implications for environmental policy and sustainability reporting by the mining industry broadly, but particularly for the gold sector.

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