The Environmental sustainability of mining in Australia: key mega-trends and looming constraints

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ABSTRACT

At first ‘sustainable mining’ could be perceived as a paradox—minerals are widely held to be finite resources with rising consumption causing pressure on known resources. The true sustainability of mineral resources, however, is a much more complex picture and involves exploration, technology, economics, social and environmental issues, and advancing scientific knowledge—predicting future sustainability is therefore not a simple task. This paper presents the results from a landmark study on historical trends in Australian mining, including ore milled, ore grades, open cut versus underground mining, overburden/waste rock and economic resources. When complete data sets are compiled for specific metals, particular issues stand out with respect to sustainability—technological breakthroughs (e.g. flotation, carbon-in-pulp), new discoveries (e.g. uranium or U), price changes (e.g. Au, boom/bust cycles), social issues (e.g. strikes), etc. All of these issues are of prime importance in moving towards a semi-quantitative sustainability model of mineral resources and the mining industry. For the future, critical issues will continue to be declining ore grades (also ore quality and impurities), increased waste rock and associated liabilities, known economic resources, potential breakthrough technologies, and broader environmental constraints (e.g. carbon costs, water). For this latter area, many companies now report annually on sustainability performance—facilitating analysis of environmental sustainability with respect to production performance. By linking these two commonly disparate aspects—mining production and environmental/sustainability data—it becomes possible to better understand environmental sustainability and predict future constraints such as water requirements, greenhouse emissions, energy and reagent inputs, and the like. This paper will therefore present a range of fundamental data and issues which help towards quantifying the resource and environmental sustainability of mining—with critical implications for the mining industry and society as a whole.

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Introduction

The phrase “sustainable mining” appears, at first glance, to be a simple oxymoron—an apparent paradox. After all, numerous famous mines have long since closed due to a finite quantity of ore able to be economically (or technologically) mined and processed at that given period of history. Yet in reality there are mines in operation today that dwarf the productive output of previous generations of mines—an evident paradox.

Mineral resources are widely interpreted to be ‘finite’ with respect to sustainable development, since metals and minerals are non-renewable (at least in human or biological time scales). The most recognised study for this view is perhaps the 1972 Club of Rome analysis ‘Limits to Growth’ (Meadows et al., 1972), which included a systems dynamic model called “World3” designed to qualitatively model the interaction of global population, social issues, environmental impacts, mineral and energy resources and the economy (including the recent 30-year update; Meadows et al., 2004). It must be pointed out that one of the major contributors to global collapse by around 2050 in the World3 model was the extent of finite resources, though even if resources were doubled this merely delayed the timing of collapse. In response, some have argued in response that economic mineral resources are not a stationary, solitary figure, but rather a function of prevailing economic, technological, social and environmental constraints (e.g. Hancock, 1993; IIED and WBCSD, 2002; Tilton, 2003).

In recent years there has been a renewed public debate about mining and its sustainability, due to strong public sentiment on environmental and social issues surrounding the mining industry in Australia and globally. The past decade in particular has seen an increasingly focused debate on the need to shift modern mining to...
a more sustainable framework, with many mining companies now reporting annually on their sustainability performance alongside financial results. The approach to describing what is “sustainable mining” varies considerably, largely dependent on whether the view is from industry, government or civil society groups. A common approach in all views is that there should be ongoing availability of resources and a productive environment and healthy community at both current and former mining sites (Cowell et al., 1999; Gordon et al., 2006).

In the build-up towards the 2002 Johannesburg Earth Summit (the ‘Ro+10’ follow-up), nine of the largest mining and metal companies established the ‘Global Mining Initiative’ to examine mining, sustainability and the performance of the industry. In 2000, they launched the ‘Mining, Minerals and Sustainable Development’ (MMSD) project. While the principal report, called “Breaking New Ground” (IIED and WBCSD, 2002), was released in 2002 for the Johannesburg Summit, the MMSD project also produced 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. The 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 crucial, a focus on the sector as a whole is necessary to examine sustainability in a thorough way.

It is also important to recognise that constraints on new mines may be social (e.g. cost, availability of skilled labour; Garcia et al., 2001), as well as the capacity of host communities), political (e.g. iron ore export bans in the 1930s), technical (e.g. forty year delay in development of the McArthur River lead–zinc project; high arsenic levels in ore at the former Armstrong nickel mine), economic (markets, supply/demand), and/or environmental in nature (e.g. delay of uranium projects; exclusion of mining in national parks) (see Mudd, 2009a). In Australia this recognition of the broader context of ‘economic’ mineral resources is embedded into the statutory Joint Ore Reserves Committee (JORC) code for reporting economic resources (AusIMM et al., 2004; Stephenson, 2001).

The continuing debate on incorporating sustainable development into the mining industry, however, does not include systematic, long-term data on mining. Data for aspects such as economic resources, ore grades, solid waste burden (tailings and waste rock) and inputs and outputs, are fundamental evidence in any assessment or quantification of the environmental sustainability of mining. Many of these historical trends have recently been compiled for the Australian mining industry (Mudd, 2009a).

Since many companies now publish annual sustainability reports, it is possible to link long-term trends in mining to key environmental aspects such as water and energy consumption, solid wastes, chemical inputs, greenhouse gas emissions and other pollutants. Collectively, these aspects are broadly referred to as ‘resource intensity’. Access to these data are critical for cleaner production and holistic life cycle analyses, both of which are foundation tools for sustainability assessments (e.g. Norgate and Rankin, 2002; Stewart and Petrie, 2006).

The most popular sustainability reporting protocol is the Global Reporting Initiative (GRI)—a coalition of the United Nations, industry, government and civil society groups (GRI, 2006). The GRI aims to achieve uniform and consistent reporting on sustainability performance, making it as routine and comparable as financial reporting. A mining sector supplement aims to facilitate improved reporting for the mining industry (a final consultation draft was released in early 2009; GRI, 2009). Under the GRI, information is reported on a range of core and voluntary indicators covering spectrum social, economic and environmental aspects. A detailed analysis of GRI-based reporting and the mining industry is given by Mudd (2009b).

Understanding and predicting the environmental sustainability challenges associated with mining requires knowledge of historical production trends as well as the relationship between production and resource intensity. These relationships can then be used in the sustainability debate which surrounds mining, including scenario development or forecasting/backcasting studies. Although social and economic issues are obviously important in understanding the sustainability of any industry, this paper will focus on the principal mega-trends and aspects of the Australian mining industry with respect to environmental sustainability. Comments on social or economic aspects are made where possible.

This paper quantifies the principal trends of Australian mining and places these within the context of the current debate on sustainable mining. A discussion of the key Australian ‘mega-trends’ and the merits of different perspectives is then presented, leading to recommendations for improved sustainability reporting to allow a better understanding and quantification of environmentally sustainable mining.

Methodology

This paper summarises the results from a more detailed study (Mudd, 2009a) combined with research on resource intensity. In brief, the study was centred around the collection of a range of data sources to compile master data sets on key trends in the Australian mining industry. The principal references used were government and industry periodicals, company annual reports, technical reports, scientific monographs and other literature. Full details, data sets and references are given in Mudd (2009a). The following annual series are presented:

- contained mineral/metal production from mining over time;
- ore grade for select minerals/metals;
- proportion of ore mined by open cut mines;
- waste rock (or overburden) mined;
- economic mineral resources over time, including average ore grade.

Further to mineral production trends, this paper also presents data for the resource intensity of new mineral/metal production. Resource intensity data are adopted from sustainability reports and combined with mine production data. The two case study metals analysed are gold and uranium, summarised from Mudd (2007b) and Mudd and Diesendorf (2008):

- energy costs per unit mineral production, with respect to ore grade and ore throughput;
- water costs per unit mineral production, with respect to ore grade and ore throughput;
- greenhouse costs per unit mineral production, with respect to ore grade and ore throughput;
- cyanide costs per unit mineral production, with respect to ore grade (gold only).

The resource intensity includes data from gold and uranium mines all over the world, with the data sets recently being updated as well as being analysed for aspects such as mine type
and energy–electricity sources. Additional recent uranium data is also obtained from Nilsson and Randheim (2008). The gold data comprises ~43.9% from Australia while for uranium it is 60.9% Australian. The global data are included since they form a more holistic view of the issues and variability, and are representative of existing and potential mines in Australia. Such global data sets

Fig. 1. Historical mineral production in Australia.
Results: key mining mega-trends

Mineral production over time is shown in Fig. 1, with black and brown coal shown in Fig. 2. Total mineral production by state and Australia is summarised in Table 1. Some states dominate in certain minerals, while several minerals are widely spread in their production between states. The production over time is often explained by seminal discoveries in Australian mining—such as Burra, Moonta-Wallaro, Bendigo-Ballarat (and later Kalgoorlie), Mount Bischoff, Mount Morgan, Broken Hill, Mount Lyell, Mount Isa, Groote Eylandt, Kambalda, the Pilbara, Weipa-Gove-Darling Ranges, Olympic Dam, Argyle and so on. Other changes in production are related to apparent field exhaustion (e.g. alluvial tin), varying economic conditions (e.g. copper, gold), government policy (e.g. iron ore), social issues (e.g. the great 18-month union strike at Broken Hill over 1919-20) or new technology (e.g. gold).

More comprehensive historical accounts of each mineral or metal are given in Mudd (2009a).

The available data compiled for ore grades are shown in Fig. 3. In general, the underlying data sets cover more than 80% of mine production for the period presented, with some metals being ~100% of reported total Australian production. As with production, ore grade trends help to explain the long-term evolution in Australian metal mining. For copper, initial mines of the 1840s–50s were in shallow high grade oxidised ores but these were quickly exhausted and by the 1880s the copper sector was moving rapidly to treat and smelt more extensive but lower grade sulfide ores. Throughout the twentieth century, the rise and fall of the average copper ore grade is related to the changing mines and their open cut/underground configuration (e.g. Mount Lyell and Mount Morgan), and the development of new mines (especially Mount Isa). Similarly, Broken Hill dominated the
lead–zinc–silver sector until Mount Isa began life, with much of the early ore being oxidised ores followed by a major shift to sulfide ores within a decade. The long-term trend for gold ore grade is a combined reflection of exploration, demand and the emergence of new technology (cyanide and its generations of processing technology, especially carbon-in-pulp or CIP). Over the past decade, the drop in nickel ore grade is due to the introduction of both large-scale low-grade sulfide mines as well as low-grade laterite mines.

The available data compiled for open cut mining, based on the proportion of ore, are shown in Fig. 4. In general, there is only minor difference between the proportion of open cut mining calculated from either the ore or mineral (uranium being the exception). For most minerals shown, there is a general trend towards increasing open cut mining. Many minerals are not shown as they have always been extracted by open cut mining (e.g. bauxite, diamonds, iron ore, manganese, mineral sands). For copper, the rise and fall and re-rise of open cut mining is due to the changing open cut/underground mine configurations at Mount Lyell and Mount Morgan, the start of Mount Isa, and the changing open cut/underground mine configurations at Olympic Dam. A critical mineral to note is black coal, which has moved from complete underground mining to 80% open cut mining over the same period which has seen exponential growth moved from complete underground mining to 80% open cut mining over the same period which has seen exponential growth.

Associated with this move to open cut mining is the ratio of waste rock to the ore mined, included as an inset in Fig. 5 (black and brown coal was included in Fig. 2). For most minerals, there is a gradually rising ratio over time (e.g. black coal, gold, copper) while for some it is relatively stable (e.g. brown coal). Note that the data presented in Fig. 5 are a minimum only, since many companies do not report waste rock. For the data compiled, no year represents all waste rock due to gaps from numerous open cut mines, while data from underground mines are extremely rare (thereby excluding the comparison of open cut/underground waste rock-ore ratios).

The available data for economic mineral resources over time are shown in Fig. 6. In general, changes over time are related to the discovery or exhaustion of major deposits as well as evolving exploration effort, technology and similar issues. The major 1960s mining boom is clearly visible, with other minerals showing increasing or stable trends. In addition, the ore grades of economic resources over time for copper, lead, zinc and uranium are shown in Fig. 7, showing a general long-term decline similar to milled ore grades.

In addition to the extent of economic mineral resources over time, it is possible to assess the years remaining for various minerals by comparing resources to annual production, the resources-to-production ratio (‘RP ratio’), given in Table 2. The RP ratio is only calculated assuming constant 2008 production and ignores increasing annual production over time. The RP ratio over time for black coal is included in Fig. 2, showing a strong declining trend in the past two decades as production has climbed significantly.

### Table 1

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Vic</th>
<th>Nsw</th>
<th>Qld</th>
<th>Tas</th>
<th>Sa</th>
<th>Nt</th>
<th>Wa</th>
<th>Aust</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bauxite (Mt)</td>
<td>0.217</td>
<td>0.235</td>
<td>408.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>197.2</td>
<td>874.3</td>
<td>1927–2008</td>
</tr>
<tr>
<td>Black Coal (raw)Mt</td>
<td>22.74</td>
<td>4,519.2</td>
<td>4,052.3</td>
<td>27.49</td>
<td>117.9</td>
<td>–</td>
<td>207.0</td>
<td>8,947</td>
<td>1829–2008</td>
</tr>
<tr>
<td>Copper (kt)</td>
<td>15.4</td>
<td>2,903</td>
<td>11,167</td>
<td>1,737</td>
<td>3,181</td>
<td>366.9</td>
<td>1,103</td>
<td>20,473</td>
<td>1842–2008</td>
</tr>
<tr>
<td>Diamonds (Mcars)</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.52</td>
<td>772.3</td>
<td>1867–2008</td>
</tr>
<tr>
<td>Gold (t)</td>
<td>2,389.1</td>
<td>885.9</td>
<td>1,375.4</td>
<td>205.5</td>
<td>65.9</td>
<td>546.9</td>
<td>6,308.2</td>
<td>11,777</td>
<td>1851–2008</td>
</tr>
<tr>
<td>Ilmenite (kt)</td>
<td>101.6</td>
<td>1,483</td>
<td>4,514</td>
<td>0.6</td>
<td>17</td>
<td>5</td>
<td>-40,927</td>
<td>-47,050</td>
<td>1934–2008</td>
</tr>
<tr>
<td>Iron Ore (Mt)</td>
<td>0.041</td>
<td>4.84</td>
<td>0.668</td>
<td>81.24</td>
<td>248.9</td>
<td>8.378</td>
<td>4,954</td>
<td>5,298</td>
<td>1889–2008</td>
</tr>
<tr>
<td>Lead (kt)</td>
<td>–</td>
<td>0.4</td>
<td>22,621</td>
<td>11,573</td>
<td>2,269</td>
<td>18.1</td>
<td>639.5</td>
<td>823.5</td>
<td>37,945</td>
</tr>
<tr>
<td>Manganese Ore (Mt)</td>
<td>–</td>
<td>76.4</td>
<td>158.4</td>
<td>-0.8</td>
<td>62.7</td>
<td>71,344</td>
<td>9,596</td>
<td>81,599</td>
<td>1946–2008</td>
</tr>
<tr>
<td>Monazite (kt)</td>
<td>–</td>
<td>–</td>
<td>22.3</td>
<td>5.5</td>
<td>–</td>
<td>–</td>
<td>170.4</td>
<td>248</td>
<td>1947–2008</td>
</tr>
<tr>
<td>Nickel (kt)</td>
<td>–</td>
<td>–</td>
<td>327.4</td>
<td>2.6</td>
<td>–</td>
<td>–</td>
<td>4,137.7</td>
<td>4,467.7</td>
<td>1967–2008</td>
</tr>
<tr>
<td>Rutile (kt)</td>
<td>191.8</td>
<td>–</td>
<td>4,771</td>
<td>4,346</td>
<td>39.8</td>
<td>6.7</td>
<td>3,169</td>
<td>12,531</td>
<td>1934–2008</td>
</tr>
<tr>
<td>Synthetic Rutile*</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>8,520</td>
<td>8,520</td>
<td>1980–2005</td>
</tr>
<tr>
<td>Silver (t)</td>
<td>55.0</td>
<td>34,084</td>
<td>35,181</td>
<td>5,776</td>
<td>333.7</td>
<td>875.1</td>
<td>2,131</td>
<td>78,435</td>
<td>1870–2008</td>
</tr>
<tr>
<td>Tin (kt)</td>
<td>13.7</td>
<td>182.3</td>
<td>180.4</td>
<td>394.4</td>
<td>–</td>
<td>6.0</td>
<td>38.0</td>
<td>814.7</td>
<td>1870–2008</td>
</tr>
<tr>
<td>Uranium (t U3O8)</td>
<td>–</td>
<td>–</td>
<td>8,893</td>
<td>197,2</td>
<td>59,848</td>
<td>115,961</td>
<td>184,714</td>
<td>1829–2008</td>
<td></td>
</tr>
<tr>
<td>Zircon (kt)</td>
<td>260.8</td>
<td>–</td>
<td>4,913</td>
<td>4,346</td>
<td>38.5</td>
<td>0.4</td>
<td>26</td>
<td>–11,226</td>
<td>19,901</td>
</tr>
<tr>
<td>Zinc (kt)</td>
<td>19.5</td>
<td>22,661</td>
<td>14,009</td>
<td>5,544</td>
<td>553.8</td>
<td>2,343</td>
<td>3,034</td>
<td>48,465</td>
<td>1883–2008</td>
</tr>
</tbody>
</table>

− Data incomplete and approximate; * Much greater than. 2008 production data are preliminary. * Synthetic rutile data for WA only from 1980 to 2005 due to changes in reporting (production started in the late 1960’s). All data sources listed in detail in (Mudd, 2009a), with state and Australian totals being approximate only and based on the best available data set.

### Results: sustainability reporting and resource intensity

#### Energy consumption—uranium and gold mining

The compiled data sets for the energy intensity of gold and uranium mining are shown in Fig. 8. The trend line included for gold is based on the best co-efficient of determination (R²) for the entire data set. The power-type regression in Fig. 8 gives the highest R², with individual regressions for open cut or underground not showing any
substantive difference. The power-type relationship between ore grade and unit energy intensity is normal in life cycle analyses (e.g. Norgate and Rankin, 2002). Average energy intensity for gold and uranium production is summarised in Table 3. For uranium, Olympic Dam's resource intensity is calculated using 20% to account for the fact it is a copper–uranium project, this being the

![Diagram](https://example.com/diagram.png)

**Fig. 3.** Historical trends in ore grades in Australia—(i) copper, nickel and uranium (top); (ii) lead, zinc and silver (middle) and (iii) gold, diamonds, iron ore, bauxite and manganese (bottom).
Fig. 4. Historical trends in open cut mining in Australia (% ore basis)—copper and nickel (left), lead–zinc–silver and uranium (right).

Fig. 5. Historical trends for waste rock and waste rock-ore ratios in Australia.
Fig. 6. Historical trends for economic mineral resources in Australia.
average proportion of revenue received from uranium over time (normal practice in life cycle assessment; Fthenakis et al., 2009).

Cyanide consumption—gold mining

The compiled data set for the cyanide intensity of gold mining are shown in Fig. 9. The power-type regression included is based on the highest $R^2$, with other options showing lower $R^2$ values, and is common in life cycle analyses. Average cyanide intensity for gold production is summarised in Table 3.

Water consumption—uranium and gold mining

The compiled data set for the water intensity of gold and uranium mining are shown in Fig. 10. Average water intensity for gold and uranium production is summarised in Table 3. All water is adopted as it is presented in sustainability reports (see later discussion, plus Mudd, 2008, 2009b).

Greenhouse emissions—uranium and gold mining

The compiled data set for the greenhouse intensity of gold and uranium mining are shown in Fig. 11. The Olympic Dam project is analysed in the same way as energy. Average greenhouse intensity for gold and uranium production is summarised in Table 3. Similarly to previous figures, there is a reasonable degree of variability in the gold data. This is partially explained by the primary electricity source, such as coal or hydro-electricity, since most hydro data plots below coal. A power-type regression for coal only gives an $R^2$ of 0.333, while for hydro the $R^2$ is 0.434 and for diesel it is 0.524 (other types give very similar or lower $R^2$ values).

There are coal and hydro-electricity data, however, which show similar greenhouse intensity for the same ore grade, suggesting that the proportion of direct and indirect energy is just as crucial in contributing to the final greenhouse intensity as energy source. The data set requires further in-depth analysis of factors such as processing type (CIP, heap leach, etc.), climate (cold versus hot), mine depth (e.g. deep South African versus shallower Western Australian gold mines), project age and duration.

Discussion

The extensive data sets and trends in Australian mining and associated sustainability analyses for resource intensity represents a unique semi-quantitative perspective on mining, and raises numerous issues with respect to sustainability and modern mining, and sustainability reporting in particular.

Fundamental mega-trends in mining: production, ore grades, wastes and resources

For almost all minerals in Australia, production continues to gradually grow over time, with some growing rapidly (e.g. copper, black coal, zinc, iron ore). Depending on the mineral, there are various reasons for this production growth. These relate to new discoveries (and mines), expansions, new technology or higher prices. The rate of growth of demand for many minerals (e.g. iron ore, manganese) accelerated in the mid-2000s in response to the strong economic expansion of China and other Asian economies.

For most metallic minerals there are long-term declines in average ore grades processed—and this is arguably terminal when
combined with increasing production. That is, since known economic resources are lower grade than present milled ore grades and the fact that lower grade deposits are often larger in contained minerals, the only way to increase production to meet rising demand is through mining even lower grades than at present. Some trends show the influence of mines being expanded, exhausted or opened, the best example being copper (such as Burra, Mount Lyell and Mount Isa). For most minerals, based on known deposits, it is hard to envisage new discoveries or mining techniques leading to ore grades rising in the future. A review of known deposits across a variety of minerals suggests that ore grades will continue to decline, but perhaps at a slower

Table 3
Weighted average resource intensity for gold and uranium production (including ± one standard deviation).

<table>
<thead>
<tr>
<th></th>
<th>Energy consumption (GJ/kg Au; GJ/t U₃O₈)</th>
<th>Water consumption (kL/kg Au; kL/t U₃O₈)</th>
<th>Greenhouse emissions (t CO₂e/kg Au; t CO₂e/t U₃O₈)</th>
<th>Cyanide consumption (kg CN/kg Au)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>149 ± 105</td>
<td>634.9 ± 1208</td>
<td>13.9 ± 12.9</td>
<td>198 ± 204</td>
</tr>
<tr>
<td>Uranium</td>
<td>273 ± 124</td>
<td>1753 ± 2798</td>
<td>26.4 ± 17.6</td>
<td>–</td>
</tr>
</tbody>
</table>

* Estimated excluding Olympic Dam.
Fig. 9. Cyanide intensity by mine type versus ore grade, including regression.

\[ y = 258.16x^{-0.6501} \]
\[ R^2 = 0.3623 \]

Fig. 10. Water intensity versus grade: gold, including regression (top), uranium (bottom left); water intensity over time for selected uranium mines (bottom right).
rate than the past. According to Mudd (2009a), the average gold ore grade processed in 2005 was \( \sim 1.94 \text{ g/t} \) whereas a compilation of economic gold resources for 2005 shows a grade of \( \sim 1.0 \text{ g/t} \).

Fig. 11. Carbon intensity versus grade: gold, including regression (top), carbon intensity versus energy cost (middle) (showing linear trend lines for coal, \( R^2 = 59.1\% \), and hydro, \( R^2 = 67.5\% \)); uranium (bottom left); carbon intensity over time for selected uranium mines (bottom right).

A critical problem with the ore grade data for iron ore, bauxite and manganese is that it represents the grade of saleable (i.e. beneficiated) product from 1952 onwards—and not the raw grade.
of as-mined ore. Reporting of as-mined ore grades is rare in these sectors. The only example for iron ore is the Savage River project in Tasmania, for which all mine and mill data are reported by the state agency. For manganese, the smaller Bootu Creek and Woodie Woodie mines report percent manganese grades but the large Groote Eylandt mine does not. The iron ore grade from 1907 to 1945 is for New South Wales only (the smaller producer) but does appear to reflect extracted iron content (see Mudd, 2009a). As such, although recent ore grades for iron ore, bauxite and manganese appear relatively stable with only a very minor decline, this reflects saleable product and not as-mined ore.

Two other principal issues related to ore grade are impurities (e.g. arsenic, mercury) and the quality or refractory nature of the mineralogy. The definition of an impurity is difficult since some metals such as arsenic are widespread in some ore types (e.g. copper, gold) and can be commercially extracted depending on market conditions. In any case, metals such as arsenic or mercury can add significant health and environmental risks in mining and processing. In Europe, the new ‘REACH’ regulations will govern impurity levels in products being delivered into the European Union (see Minns, 2008).

Over time it is relatively common that more refractory types of ores have been developed in Australia. This is reasonably well documented for the gold sector, especially the processing of clay-rich laterite ores by CIP processing using salt-rich brines (Mudd, 2007b). For lead–zinc–silver, each transition from Broken Hill to Mount Isa to McArthur River has seen the ore become more refractory, especially for the very fine-grained McArthur River ore (Mudd, 2007a). Similarly, the recent development and implementation of new high pressure acid leach (HPAL) process technology in the late 1990s has made extensive but refractory nickel laterite deposits viable to mine and process—though at a higher resource intensity compared to sulfide projects (Jessup and Mudd, 2008).

The ability to consider refractory or ‘impurity-rich’ ores as an economic mineral resource will continue to be a function of technology, economics and environmental conditions, although exceedingly little such research is available.

The principal mining technique has, since about 1950, moved from underground to open cut, especially for black coal, nickel and gold. For several minerals, open cut mining has facilitated substantive project scales to be established in provinces such as the Pilbara, the Hunter Valley, Kalgoorlie and the Darling Ranges. For some sectors, such as copper and lead–zinc–silver, significant underground mining still occurs. In terms of material moved, it is clear that open cut mining is used for the vast majority of ore and waste rock extracted annually across the Australian industry. The dominance of open cut mining looks set to continue for at least a decade, provided the price of transport fuels remains competitive (most critically diesel; see Graham, 2008). The recent decline in open cut mining for black coal, from a peak of 78.1% in 2004 to 75.7% in 2008, may suggest the beginning of a trend back to underground mining—possibly reflecting the exhaustion of near-surface coal resources and the need to mine deeper. For some metals, such as copper, gold or uranium, there is a view that future mineral deposits will be discovered deeper and it is unclear whether this will eventually lead to a major shift back to underground mining or even larger open cut mines (such as the ‘mega-pits’ planned for the Olympic Dam expansion and the potential Mount Isa pit).

In conjunction with the major shift to open cut mining, the extent of waste rock is now likely to be at least equivalent to the amount of ore mined and for many minerals is up to several times higher. While a major proportion of this waste rock is likely to be relatively chemically benign, a major quantity is likely to present challenges during operations and rehabilitation due to sulfides present, climate regimes, sensitive environments or communities being adjacent or a combination of these factors. At present, there is no compulsory requirement for public reporting of the waste rock mined annually, nor it's nature (such as potentially acid-forming).

The rehabilitation of mined land and associated mine wastes is now a major legal requirement and legitimate community expectation—but the long-term success of engineered rehabilitation works is not guaranteed. The scale of waste rock movement present now in the mining industry far exceeds that at historic mines, and therefore the previous generation of rehabilitated mines cannot be used with certainty to be assured of future success. For example, the Commonwealth Government spent some $25 million on rehabilitation of the former Rum Jungle field in 1980s yet in 2007 the adjacent Finniss River is still heavily polluted by acid mine drainage leaching from rehabilitated waste rock dumps (see Mudd and Patterson, 2008)—see Fig. 12. The engineering principles of unsaturated flow mechanics used to design the soil covers at Rum Jungle still form the basis for management and rehabilitation of high risk AMD wastes today, and so understanding the performance of the site is crucial in the industry’s long-term efforts in addressing this major environmental risk (see Lottermoser, 2007). It is not assured that scaling up the performance of rehabilitation of older sites to much larger modern sites is realistic, especially given different operating conditions. Given the growing scale of modern mine waste, even if only 1% of wastes continue to cause pollution (i.e. rehabilitation is 99% perfect), this amounts to tens to hundreds of millions of tonnes leaving a lasting environmental legacy. Caution needs to be applied in predicting the trajectory of long-term rehabilitation behaviour.

With respect to economic resources, most commodities show gradually increasing quantities, with distinct periods of major increases evident at different times for particular minerals (e.g. 1960s for iron ore, 1980s onwards for gold, 1990s onwards for rutile and zircon). For copper, major new discoveries continue to be made (e.g. Prominent Hill and Carrapateena in South Australia).

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Fig. 12. Acid mine drainage from the rehabilitated White’s waste rock dump (left, note the active seepage flows) and the adjacent bed of the Finniss River in the dry season (right), Rum Jungle, July 2007.
and there are brownfield increases to existing deposits or mines (especially Olympic Dam and Mount Isa). Nickel resources have increased substantially from the mid-1990s due to the inclusion of laterite ore resources as economic following the emergence of new HPAL technology (Jessup and Mudd, 2008; Mudd, 2007a). In comparison, uranium has primarily increased over time due to increased drilling and the expansion of economic resources at known deposits (principally Olympic Dam, plus Ranger to a lesser extent), although some new deposits are being discovered (e.g. Beverley Four Mile).

According to Geoscience Australia, "it is notable that resources levels for major commodities like black coal, iron ore and base metals have plateaued" (pp. 10, 2006 Edition, GA, var.). For black coal, however, the amount of 'economic resources' is commonly only that existing in mine leases and has had sufficient mine planning to classify it as mineral resources under the JORC code. Analysis of geologic information and historical assessments of possible in situ coal present in Queensland and New South Wales alone suggests a potential magnitude of some hundreds of billions of tonnes (pp. 21–24, Mudd, 2009a)—compared to the 2008 estimate of 39.2 Gt. The same basis exists for brown coal, iron ore and bauxite. For metallic commodities, a pattern of rising economic resources has been maintained, while it is common for sub-economic resources to be further evaluated and upgraded to economic resources over time (either through expanded resources, improved technology, market conditions, etc.). This aspect of mineral resources is shown in Table 2, with sub-economic resources commonly being similar to or greater than economic resources.

The fundamental questions which follow from this are not whether mineral resources are 'finite' but—(i) what are the future conditions under which mineral resources are likely to be considered 'economic'?; (ii) what are the associated social and environmental costs of mineral production?; and (iii) what are the critical links between economic, social and environmental aspects of mining? The emergence of sustainability reporting and associated data affords the opportunity to analyse these questions more thoroughly.

**Sustainability reporting and resource intensity: comprehensiveness and transparency**

The data presented on sustainability reporting, and estimates of the resource intensity per unit mineral production demonstrates that resource intensity is sensitive to the ore grade being processed. This is expected, since lower ore grade requires more ore to be mined and processed to maintain a constant level of production. The data suggests that larger projects can achieve economies of scale, but often at the expense of greater total resource requirements. The compilations presented on gold and uranium mining were effectively sector level views. Aspects such as open cut, mixed or underground mining were included for gold (but not age, depth or project scale), while processing type such as heap leaching versus carbon-in-pulp milling, ore types, or tropical, temperate or arid climates, etc., were not included as potential factors (commonly due to lack of reporting or sufficient details). A review of the data does not easily suggest or indicate the degree to which these factors could influence the resource intensity for gold or uranium production—there is considerable more research required in advancing the understanding of the complex factors which underpin the variability in Figs. 8–11. When the ore grade sensitivity of resource intensity is considered in light of declining ore grades, and potentially increasingly refractory ores, this suggests that the resource intensity of mineral production in the future will increase given existing technology. There has been a long-term evolution of technology in the mining industry, including greater mechanisation which has improved labour productivity and economics, and the inevitable march of technological progress will almost definitely continue—but the question remains open whether future innovation will deliver new technology at a lower resource intensity.

Considering resource intensity in light of sustainability reporting, there are a number of issues which are apparent with respect to the Global Reporting Initiative. Under the GRI protocol (GRI, 2006) and the draft mining sector supplement (GRI, 2009), the primary indicator for solid mine wastes is ‘EN22’, which is the “total weight of waste by type and disposal method”. It clearly includes landfill wastes (putrescible material), metal scrap, inert solids (e.g. cement), construction waste, solid chemical wastes, used tyres, and the like. There is widespread inconsistency, however, as to whether EN22 explicitly includes solid mine wastes such as tailings and waste rock. The final draft mining sector supplement proposes that only “hazardous” mine wastes should be reported after a site-specific risk assessment under a specific indicator ‘MM3’ (pp. 42 and 46, GRI, 2009). Therefore some companies who use the GRI as their sustainability reporting basis do not publicly disclose tailings and waste rock data under EN22 while some companies give variable levels of information.

![Fig. 13. Recent examples of tailings and waste rock reporting under GRI’s solid waste indicator (EN22).](image-url)
To illustrate this, examples of solid waste reporting are shown in Fig. 13, and highlight the variable way in which data are reported. For one case the data does not distinguish between tailings or waste rock—which are fundamentally different in terms of their scale and nature with respect to long-term environmental risks. Curiously, some companies report tailings and waste rock data as part of financial performance while others do not. While some companies do acknowledge and discuss the nature of their solid wastes, such as potentially acid-forming, quantitative data in sustainability reports are exceedingly rare—the vast majority of companies do not. At present, significant further research is needed to fully characterise the extent and nature of tailings and waste rock, and especially the long-term success of rehabilitation measures on reactive mine wastes.

For energy, some companies report totals only, with no explanation of energy sources or the split between direct and indirect energy, while others give detailed breakdown by several energy sources. Further to this, some companies give consumption in mass or volume terms and do not present energy in consistent metric units such as gigajoules (GJ) or the relevant conversion factors for their respective energy components (allowing for differences between various continents and regions). Consistent, accurate energy reporting is imperative to ensure accurate life cycle analyses.

Recently, it was shown that the energy intensity of the Australian mining industry had increased by 3.7% per year from 1989/90 to 2005/06 (Sandu and Syed, 2008). Importantly, it was noted that energy costs in mining were exacerbated by the increasing energy costs of drilling deeper during exploration as well as the problem of lower grade ores—adding further evidence to the increasing energy costs for unit mineral production. Furthermore, energy savings were outweighed by higher energy requirements.

Similarly for greenhouse emissions, complete data are often not reported (despite being core GRI data), or the conversion factors for carbon costs not referenced or noted (which do vary from region or source, especially electricity source). This is, without doubt, part of the reason for the variability in Fig. 11. Given declining ore grades and the inverse relationship between ore grades and energy/greenhouse intensity, it can be expected that greenhouse emissions will be a growing challenge for the mining industry. This is especially pertinent given the current debate concerning emissions trading systems, carbon taxes or other measures to reduce greenhouse emissions and address climate change. If government and industry policy response to climate change was to foster the renewable energy industry, this could change the nature of CO2-gJ relationships considerably, especially if transport fuels such as biodiesel became prevalent.

With respect to water and the data in Fig. 10, there are major variations in reporting despite the clear intent of EN8-10. Specifically, some projects clearly confuse ‘raw’ water withdrawn from a water resource with recycled or reused water while others distinguish such aspects but only report ‘raw’ water consumption. The resultant assessment of water costs is therefore only a fraction of the true ‘embodied water’ costs (Mudd, 2008, 2009b). The trends of water intensity over time for uranium in Fig. 10 show a commonly increasing or significantly variable trend per unit production (AU/1U3O8), while also showing either stable or declining intensity per ore processed. This is an evidence for the effects of declining ore grades over time, which almost all uranium projects have during this period.

A critical issue for water resources which is not included in GRI indicators is the quality of water consumed and/or recycled. The volume of water used is critical but this cannot be considered in isolation from water quality, principally in terms of salinity but also trace metals or nutrients. For example, numerous mines in arid central Western Australia utilise hyper-saline water resources (commonly groundwater and, to a lesser extent, surface waters) with a salinity higher than seawater (e.g. Norgate and Lovel, 2006). The varying quality of water resources used for different mines makes the equivalent water costs a vexed issue (see Cote and Moran, 2009; Mudd, 2008). The inconsistencies in reporting total and recycled water consumed in mineral production and water inventories, as well as the varying quality of water resources and significantly different project configurations could help to explain the scatter and variation in the three graphs in Fig. 10.

As an additional or voluntary indicator, GRI allows for the reporting of impacts on water resources associated with water extraction for mining. A challenging issue in this regard is contained minesite water inventories, which are often considerably larger than water consumed in ore processing and associated activities. For example, the Ranger uranium project commonly has a total minesite water inventory in engineered retention ponds or tailings facilities which is greater in volume by one to two orders of magnitude than reported annual water consumption (which, curiously, is only drinking water and not process water). The total extent of impacts on water resources, either in hydrologic, ecological or water quality terms, will vary widely between mine sites and climates, though it remains critical to consider these combined and often cumulative effects in any assessment of the ‘embodied’ water in mining.

Additionally, many companies reporting data over time fail to explain abrupt increases or reductions at a given mine. For example, one gold mine reported a change in greenhouse emissions from ~0.18 Mt CO2-e/year (8 years) to ~1 Mt CO2-e/year (2 years) and then in the following year subsequently changed this 2 years of data to ~0.1 Mt CO2-e/year—but with no explanation or basis (e.g. calculation or publication error). This can sometimes be related to corporate takeovers or merger activity leading to new policies or methodologies for compiling data, but this is rarely explained and justified in subsequent reports. Such problems in reporting are often despite use of the GRI, raising serious issues of governance and highlights the strong need for external auditing.

Finally, some companies report corporate totals only under GRI and not site-specific data. For diversified miners with multiple commodities (e.g. BHP Billiton), this makes it impractical to analyse reported data—especially considering the continuing growth in production which invariably leads to increased inputs and outputs.

As a voluntary protocol, the GRI is helping to improve the breadth, depth and consistency of sustainability reporting and associated data, but there remain many areas in which mining companies can improve their internal processes and external standards.

In Australia, the statutory National Pollutant Inventory (NPI) considers only those emissions of pollutants which are effectively released to the environment and defines waste rock and tailings facilities as land transfers only (pp. 30–31, NPI, 2001)—leaving waste rock and tailings data outside the scope of reportable NPI emissions (though any escape from a waste rock or tailings facility would still be reportable). This is a critical weakness in the NPI, as both tailings and waste rock have the potential to become major point sources of listed pollutants such as cyanide and metals. An online search of the NPI facilities database (www.npi.gov.au) reveals that some major sites of acid mine drainage (e.g. Mount Lyell, Tasmania) are included while others are not (e.g. Mount Morgan, Queensland). Given the vast quantities of mine wastes now produced annually, there is a substantive quantity of listed NPI pollutants contained within tailings and waste rock yet they...
are excluded from, or at least poorly addressed by, such accounting and reporting systems. Two final issues of note with respect to sustainability reporting are those of intellectual property (IP) and competitive advantage. It is possible that disclosure of all relevant GRI data could, in particular circumstances, divulge either sensitive IP or affect the competitive position of a company. These are important considerations with respect to the ongoing viability of a specialised process technology or company. However, the overall trend in mining, as well as many other industry and government sectors, is towards greater reporting, transparency and accountability (e.g. Mudd, 2009b; Yongvanicha and Guthrie, 2005). Given the prominence of environmental issues in the public sphere (e.g. energy, climate change and water), and the concerns and criticisms often raised with regards to the mining industry, it is important to be demonstrating sound evidence for company and industry performance—and sustainability reporting is a viable mechanism to achieve this.

Combining production and environmental sustainability for mining

When the trends of long-term growth in mineral production are combined with an increasing resource intensity, this means that inputs and outputs will rise at a faster rate than production alone. There are substantial implications from this, such as:

- increased demand for diesel when the world is debating the reality of ‘peak oil’—leading to fundamental questions concerning both supply as well as the costs of future supply;
- rising greenhouse emissions when many governments are planning or implementing emissions trading schemes (or a carbon tax) as a major international policy response to the risks of climate change;
- the need to incorporate renewable energy sources into the mining industry more rapidly than is presently the case as part of an industry response to greenhouse emissions issues;
- growth in demand for water, both in terms of land use but especially in terms of consumptive use;
- comparing the resource intensity of new mineral production versus recycling and more efficient use, or both;
- strong growth in mineral demand from rapidly developing countries, especially China but also India (and South America and Africa in the near future), continuing to place substantive pressure on economic resources for most (if not all) commodities.

Consider Australian copper production as a case study. Based on the production data in Fig. 1, it is possible to fit exponential or power-type regressions either to the entire data set or production since 1950. For the entire data set, the \( R^2 \) values are 0.716 and 0.715 for exponential or power-type regressions, respectively. If only production since 1950 is used, the time that the Australian copper industry began to grow substantively, the respective \( R^2 \) values are higher at 0.926 and 0.936. The predicted production in 2030 and 2050 is shown in Table 4, varying from 1.11 to 3.81 Mt Cu/year in 2030 to 11.95 Mt Cu/year in 2050. Based on the extent of economic copper resources, the cumulative production (Table 4) represented by these predictions is certainly within reach (cf. Table 2).

Finally, Norgate and Rankin (2002) used life cycle assessment to estimate the relationship between total greenhouse emissions and copper ore grade, shown in Fig. 14. At Australia’s average 2008 ore grade of 0.95% Cu (cf. Fig. 3), this gives an estimate of greenhouse emissions of 8.7 or 8.9 t CO\(_2\)-e/t Cu from pyrometallurgical or hydrometallurgical processing, respectively. Projecting the decline in ore grades to 2030 and 2050, using a power regression (\( R^2 = 0.714 \); exponential is 0.708), gives estimated grades of 0.57% and 0.40% Cu, respectively. By 2050, therefore, the unit greenhouse emissions could reach 18.6 or 13.3 t CO\(_2\)-e/t Cu from pyrometallurgical or hydrometallurgical processing, respectively. As shown in Table 4, this means that total greenhouse emissions for the copper sector alone of the

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<td>30.80</td>
<td>169.5</td>
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\(^a\) Greenhouse emissions based on projected ore grade decline to 0.57% Cu and the use of pyrometallurgical processing.

\(^b\) Greenhouse emissions based on projected ore grade decline to 0.40% Cu and the use of hydrometallurgical processing.

\(^c\) Greenhouse emissions based on projected ore grade decline to 0.40% Cu and the use of pyrometallurgical processing.
Australian mining industry could reach between 15.3 and 169.5 Mt CO₂-e if all copper was produced using pyrometallurgy—compared to about 7.8 Mt CO₂-e at present. Thus greenhouse emissions could easily double (or more) over the timeframe that the public sphere is debating the merits of reductions of the order of 50–80% from 2000 levels. If such targets are to be achieved, this would mean a maximum level of emissions for copper production in 2050 of between 2.4 and 3.8 Mt CO₂-e—meaning effective cuts in unit emissions ranging from a best case of 75% (15.3–3.8 Mt CO₂-e) to a worst case of 98% (169.5–2.4 Mt CO₂-e).

These estimates are, by their nature, coarse and are furnished to provoke discussion on what, ultimately, is one of the most fundamental challenges to the environmental sustainability of the mining industry in Australia—greenhouse emissions and climate change. In addition, not surprisingly, are issues around increasing solid wastes, competition for water, peak oil, recycling, social constraints, economics and markets, technological innovation and so on.

An important part of the solution could be to increase the rate of metals recycling, as this is commonly of less energy and emissions intensive. The recent evolution of and current configuration of the mining industry, however, is largely separated from metals recycling—with most mining companies, such as Rio Tinto, BHP Billiton, Vale, Anglo American, Xstrata and others, being primary producers and not being involved in metals recycling in any meaningful manner. One notable exception is Swedish miner Boliden, who operate one of Europe’s largest metals recycling and “e-waste” smelters (see Mudd, 2009b).

In the longer term, it is difficult to predict the configuration of the mining industry given the complexity of factors discussed (e.g. will heap leaching and hydrometallurgy become more dominant due to its lower emissions intensity?). It is clear that various environmental constraints will prove a constant and growing challenge, and that ‘business as usual’ will not meet the known challenges, especially with respect to energy sources, consumption and greenhouse emissions.

Summary and conclusions

Moving from a production philosophy through improved environmental management to now embracing the ‘triple bottom line’ of sustainability—social, economic and environmental components—the debate and the performance of the modern mining industry, both in Australia and globally, has clearly made important progress over recent decades. This paper has presented ongoing research into quantifying and understanding various strategic aspects of the environmental sustainability of mining in Australia, especially the emerging sustainability reporting regimes becoming increasingly adopted by mining companies.

In terms of the major trends in modern mining, a number of fundamental aspects have been shown:

- **Substantially increasing production**—almost all minerals and metals show strong to near exponential growth over time, especially over the past three to four decades;
- **Declining ore grades (or quality)**—while early mines processed rich oxide ores, average industry grades for most metals and minerals are now commonly much lower, with known economic resources suggesting this decline in ore grades will gradually continue. In addition, the quality (mineralogy) of mineral deposits are generally becoming more complex and difficult to process;
- **Open cut mining**—since the mid-twentieth century there has been a major shift from underground to open cut mining, especially in some sectors such as coal, gold and nickel, while others have always been entirely open cut (e.g. iron ore, bauxite, mineral sands);
- **Waste rock**—combined with the significant increase in open cut mining, there has been a near exponential increase in the waste rock excavated in modern mining. For most metals and minerals the quantity of waste rock excavated is significantly higher than the ore processed, and this ratio is increasing over time—presenting a major and growing challenge in mine rehabilitation;
- **Economic resources**—although often perceived as ‘non-renewable’, the extent of economic mineral and metal resources has often increased over time in Australia, though some appear to have stabilised. Growing production continues to exacerbate pressure on remaining economic resources as well as forcing a gradual shift to lower quality or more refractory deposits. Whether this validates the ‘Limits to Growth’ approach is a matter of perspective, since it is possible to conclude that mineral resources are, in general, still growing, or that the time of limited remaining mineral resources is getting closer;
- **Sustainability reporting**—the emergence of sustainability reporting protocols, such as the voluntary Global Reporting Initiative or the statutory National Pollutant Inventory, are helping to improve the transparency of modern mines, though there still remains clear reluctance to explicitly report all relevant data such as waste rock, tailings, energy, cyanide and water consumption, greenhouse emissions, or other aspects;
- **Resource intensity**—the modern solid waste burden of metals and minerals is substantive, and continues to increase. Additionally, the resource intensity, in terms of inputs and outputs, is significant and sensitive to ore grade, leading to the realisation that the resource intensity is likely to gradually increase in the future as mines shift to lower grade and possibly more refractory deposits (proving an assumption of the Limits to Growth). This makes comprehensive sustainability reporting even more critical. It is also important to consider resource intensity in conjunction with other costs such as capital and labour.

This paper has presented a wide range of data sets on the Australian mining industry as well as various issues affecting the resource intensity of unit mineral production. Fundamentally, the vast scale of modern mine waste presents significant engineering challenges to meet an ever more complex array of environmental requirements, social expectations, corporate policies and statutory demands. The emerging sustainability reporting protocols will facilitate ongoing improvement and transparency, but consistency needs to be improved. Although it may be possible to find new mineral deposits in the future, with improved technology or favourable economics facilitating the processing of higher cost resources, it is the environmental cost which will, in the medium to longer term, govern the real availability of metals and minerals. On this basis, it is possible to claim that the ‘Limits to Growth’ approach is both right and wrong—in the sense that economic mineral resources commonly continue to increase over time but right in the fact that mineral resources are becoming increasingly costly from an environmental perspective. This is the classic proverb of the glass being ‘half-full’ versus ‘half-empty’—and the evidence in this paper shows the importance of looking at historical trends to believe the glass is half-full, or using these trends to project future scenarios to believe the glass is half-empty and declining at an increasing rate. It is clear that various environmental constraints will prove a constant and growing challenge, and that ‘business as usual’ will not meet the known
challenges, especially with respect to energy sources, consumption and greenhouse emissions.

In summary, the vast scale of modern mining, mine wastes and existing and future resource intensity will continue to challenge the sustainability of the industry and requires eternal vigilance by all involved—governments, shareholders, communities and industry alike.

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