

TOWARDS QUANTIFYING THE SUSTAINABILITY OF MINING IN AUSTRALIA : LINKING PRODUCTION TO SUSTAINABILITY REPORTING AND BEYOND

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ABSTRACT

At first 'Sustainable Mining' is often perceived as a paradox - minerals are widely held to be truly 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, scientific knowledge and so on – predicting future sustainability is therefore not a simple task. This paper will present the results from a landmark research report 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 (eg. flotation), new discoveries (eg. uranium), price changes (eg. gold), 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 quality, impurities), increased waste rock and potential liabilities, known economic resources, potential breakthrough technologies, and broader environmental constraints (eg. carbon costs). For this latter area, many companies now report annually on sustainability performance – facilitating analysis of sustainability with respect to production performance. By linking these two commonly disparate aspects – mining production and environmental / sustainability data – it becomes possible to better quantify sustainability and predict future environmental constraints such as water requirements, greenhouse emissions, energy and reagent inputs, and the like. This paper will therefore present a range of fundamental issues in moving towards quantifying the resource and environmental sustainability of mining - with critical implications for the mining industry and society as a whole.

1 Introduction

The phrase "sustainable mining" appears, at first glance, to be a simple oxymoron – an obvious 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 apparent paradox.

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 civic groups.

The continuing debate on incorporating sustainable development into the mining industry, however, lacks systematic data analysis of current and historical mining activities. Data for aspects such as economic resources, ore grades, solid waste burden and environmental inputs and outputs, is fundamental evidence in any assessment or quantification of sustainability for mining.

Many of these trends have recently been assessed and compiled for the history of the Australian mining industry in, arguably, the first comprehensive study ever completed for Australia (Mudd, 2007a).

In addition, given that many companies now publish annual sustainability performance reports, it is possible to link historical and current trends in mining to key environmental aspects such as water and energy consumption, solid wastes (tailings, waste rock), chemical inputs, greenhouse emissions and other pollutant outputs. Collectively, these aspects are known as the resource intensity, eco-efficiency or environmental cost. For this paper, we will use the first phrase (resource intensity), as this is more consistent with life-cycle methodology (and arguably more neutral).

This paper does not seek to develop a new model of sustainability for the minerals industry, rather, it quantifies the principal trends of Australian mining and places these within the context of the current debate on sustainable mining. When combined with the compiled data for resource intensity, the paper provides a compelling basis for understanding the sustainability of mining. A discussion of the key Australian trends and the merits of different perspectives will then be presented, leading to some recommendations for improved sustainability reporting by the mining industry to allow a better understanding and quantification of sustainable mining.

The paper is the first truly systematic quantification of these trends and issues in the Australian mining industry, and challenges the conventional qualitative debate concerning 'sustainable mining'.

2 Sustainable Development and Modern Mining – A Brief Review

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 1950, there has been a wide-ranging debate about the sustainability of modern mining. This section presents a succinct review of this debate.

The most common starting point for 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 & 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 (eg. 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 to argue the perceived non-renewable nature of mineral resources (eg. 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 (eg. Hancock, 1993; IIED & WBCSD, 2002; Trubetskoi et al., 2002; Tilton, 2003; Yua et al., 2005).

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 is select data available in national mining industry periodicals (eg. Australia – GA, 2006; Canada – NRC, various; United States – USBM, various and USGS, various). However, these are not complete as they do not present data for ore tonnage, ore grade, contained metal and associated waste rock nor the social and environmental impacts and constraints associated with mining (eg. water, greenhouse emissions, energy, regulatory issues, etc).

It is important to understand the nature of mineral resources, since issues such as ore grades, impurities (eg. arsenic, mercury), waste rock, geological and mining constraints, technological requirements as well as 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 Committee (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). In the current so-called 'super-cycle' mining boom, driven mainly by China's rapidly increasing demand for minerals, this primary concern is being raised again (eg. Gordon et al., 2006; Cohen, 2007).

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 (eg. gold from government stockpiles or recycling). 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), but particularly for the developing world (eg. 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, social and economic risks. The primary difference now is that the issue is of a truly global scale and concern rather than Agricola's locale of central Europe. For particular metals some advocates argue passionately that there is net detriment or at best no net benefit, such as gold mining (see Ali, 2006; Whitmore, 2006). Other controversial minerals also come under this notion (eg. uranium).

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 (eg. an Environmental Protection Agency). The mining industry accepted the legitimacy of this changed landscape and worked to improve industry standards and performance throughout the 1970s to 1980s, primarily to meet legal requirements but also to ensure social acceptance of existing and future mines (Hancock, 1993; 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 in public and policy sentiment.

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, various; WMC is now part of BHP Billiton). 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 (PD, various). WMC, Placer Dome and other companies relied on policies, performance measures and reporting procedures developed internally – though broadly within a 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 & Bossilkov, 2004). Another example is Newmont Mining Corporation, which has moved from largely qualitative sustainability reports to their 2005 sustainability reports using the GRI (see below) and providing detailed quantitative data for all of their mine sites.

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 project was called the 'Mining, Minerals and Sustainable Development' (MMSD) project (IIED & WBCSD, 2002), and its final report was formally launched at Johannesburg. The MMSD project 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 examine sustainability in a thorough way.

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 & Basu, 2003; van Berkel & 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, amongst others. They provide a broader set of indicators than those developed by companies such as WMC and Placer Dome, and are derived from the various principles for sustainability, including the precautionary principle, inter- and intra-generational equity, biodiversity, pollution minimisation and maintenance of various forms of capital (eg. natural, economic, human).

A broader initiative for sustainability reporting and indicators is 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 the GRI. A specific mining sector supplement, released in pilot form in 2005 (GRI, 2005), aims to facilitate improved and more relevant sustainability reporting for mining.

A principal benefit of the evolving reporting regime is the increasing abundance of data available to assess the resources required for new mineral production. This allows estimation of water, energy and chemicals requirements as well as resultant wastes and pollutant emissions (eg. 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 holistic life-cycle analyses, both of which are foundation tools for sustainability assessments (eg. Guerin, 2006; Norgate & Rankin, 2002; Stewart & 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 & Petrie, 2006).

Predicting sustainability challenges associated with mining requires knowledge of historical production trends as well as the relationship between production and resource intensity. As an example, one key production trend which is reasonably well recognised is that of declining ore grades (eg. Craig & Rimstidt, 1998; Müezzinoğlu, 2003; Ruth 1995). Despite the global scale and reach of the modern mining industry, 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 mining and to link it to production performance reporting. These relationships can then be used in the sustainability debate which surrounds mining. The remainder of this paper compiles and analyses these data sets for the Australian mining industry.

3 Methodology

This paper summarises the results from a more detailed study (Mudd, 2007a). 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 periodical series on the mining industry by government and industry, company annual reports, reports, monographs and other technical literature (journals and conferences). For this paper, the following aspects are presented :

- **Annual Mine Production** : contained mineral / metal production from mining over time;
- **Annual Ore Grade** : ore grade for select minerals / metals (copper, lead-zinc-silver, gold, nickel, uranium, diamonds);
- **Annual Open Cut Mining** : ore mined by open cut mines;
- **Annual Waste Rock (Overburden)** : waste rock (or overburden) mined, primarily open cut mines (underground mines were included where data was available, though this was rare);
- **Annual Economic Resources** : assessments of economic mineral resources over time;

Full details are given in Mudd (2007a), including the extensive range of references utilised.

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

- **Energy Costs** : energy costs per unit mineral production, with respect to ore grade and ore throughput;
- **Water Costs** : water costs per unit mineral production, with respect to ore grade and ore throughput;
- **Greenhouse Costs** : water costs per unit mineral production, with respect to ore grade and ore throughput;
- **Cyanide Costs (gold mining only)** : cyanide costs per unit mineral production, with respect to ore grade.

The resource intensity aspects include data from gold and uranium mines all over the world.

4 Results : Key Mining Trends

All mineral production over time is shown in Figure 1, with black and brown coal shown in Figure 2. Total mineral production by state and Australia is summarised in Table 1. Some states dominate in certain minerals (eg. Western Australia and nickel, Victoria and brown coal), while some minerals are widely spread in their production between states (eg. copper, gold). The production over time is often explained by seminal discoveries in Australian mining – such as Burra, Bendigo-Ballarat (and later Kalgoorlie), Mt Bischoff, Mt Morgan, Broken Hill, Mt Lyell, Mt Isa, Groote Eylandt, Kambalda, the Pilbara, Weipa-Gove-Darling Ranges, Argyle and so on. Other changes in production are related to apparent field exhaustion (eg. alluvial tin), varying economic conditions (eg. copper), government policy (eg. iron ore) or new technology (eg. gold). More comprehensive historical accounts of each mineral or metal are given in Mudd (2007a).

The available data compiled for ore grades is shown in Figure 3. In general, the underlying data sets cover more than 80% of mine production for the period presented, with some metals being close to 100% of reported total Australian production, and the ore grade trends are therefore a good illustration of that particular metal. 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 high grade oxidised ores but these were quickly exhausted and by the 1880s the copper sector was moving rapidly to treat and smelt sulfide ores which were more extensive but of lower typical ore grade. Throughout the twentieth century, the rise and fall of the average copper ore grade is related to the changing mines and their configuration (eg. Mt Lyell and Mt Morgan), and the development of new mines (especially Mt Isa). Similarly, Broken Hill dominated the lead-zinc-silver sector until Mt Isa began life, with much of the early ore being oxidised ores followed by a major shift to sulfide ores. The long-term trend for gold ore grade is a combined reflection of exploration, economics (i.e. price and demand) as well as the emergence of new technology (cyanide milling and its different generations of processing technology). Over the past decade, the drop in nickel ore grade is due to the introduction of both large-scale low-grade nickel sulfide mines as well as low-grade nickel laterite mines.

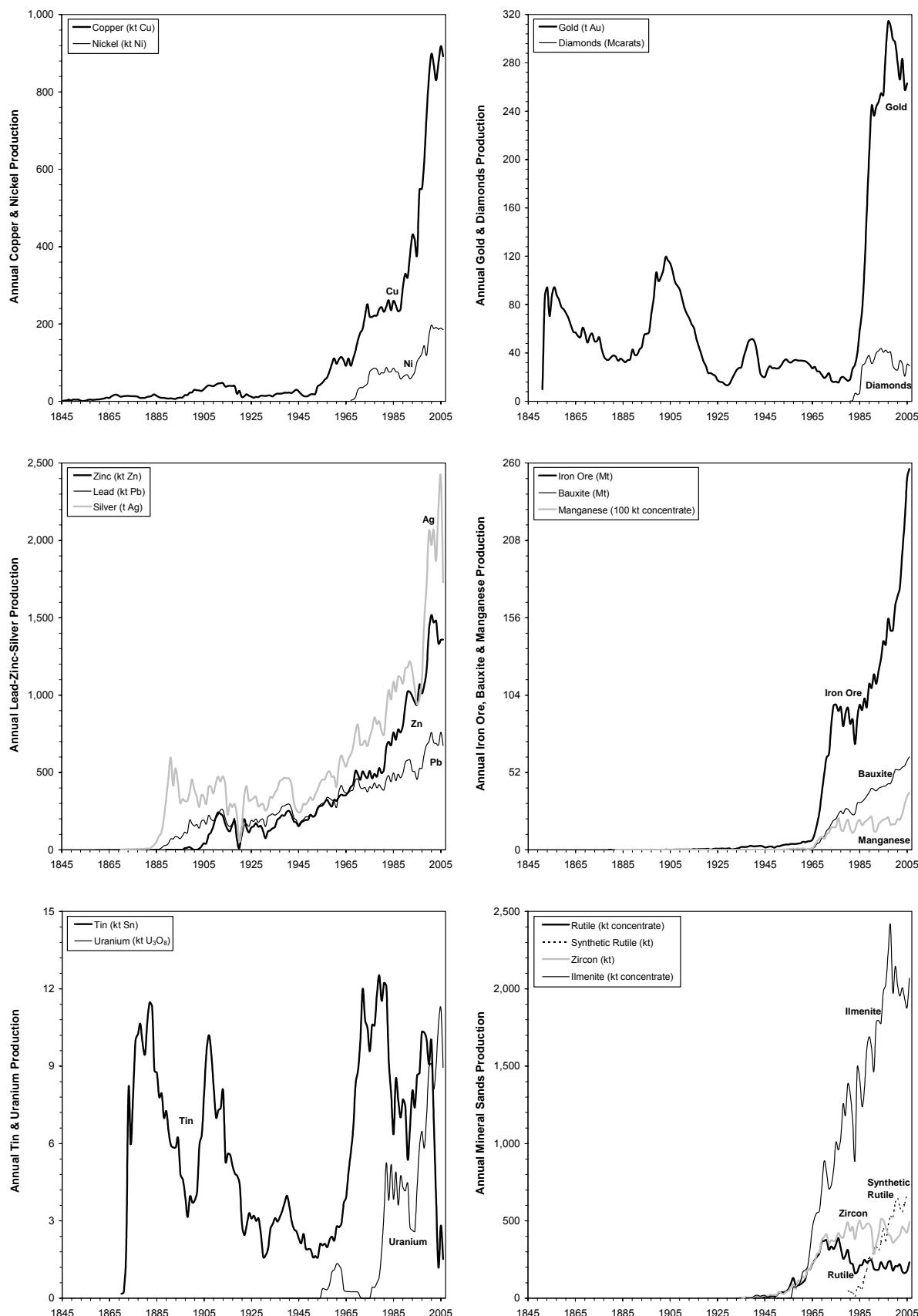


Figure 1. Historical mineral production in Australia (adapted from Mudd, 2007a)

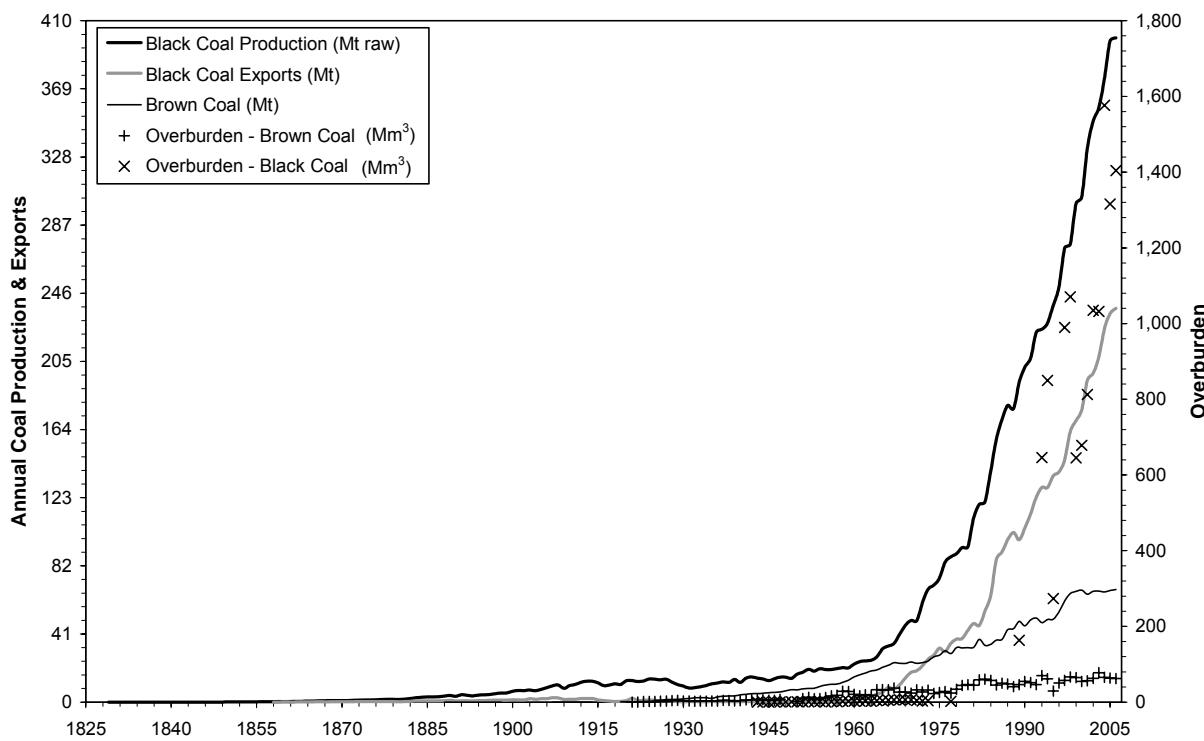


Figure 2. Historical black and brown coal production in Australia (adapted from Mudd, 2007a)

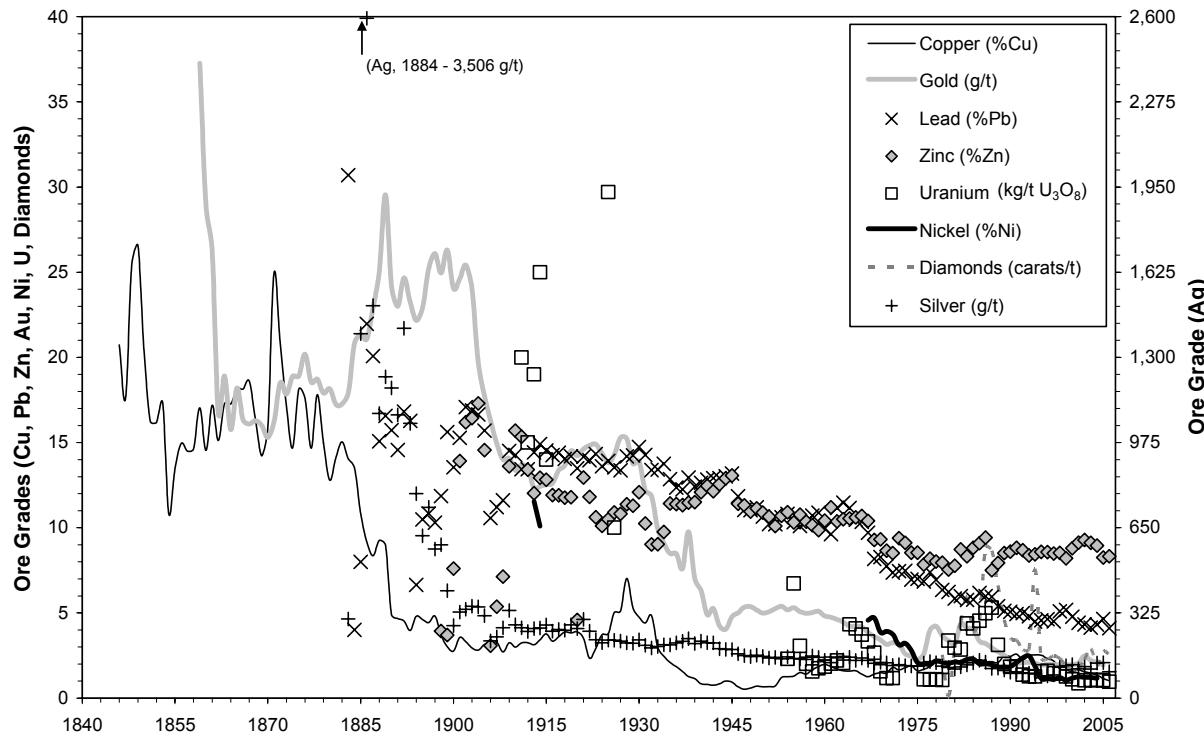


Figure 3. Historical trends in metallic ore grades in Australia (adapted from Mudd, 2007a)

Table 1. Total Mineral Production by State and Australia (adapted from Mudd, 2007a)

	Units	VIC	NSW	QLD	TAS	SA	NT	WA	Aust	Period^P
Bauxite	Mt	0.217	0.235	370.0	0	0	~186.6	~791	~1,349	1927-2006
Black Coal (raw)	Mt	22.7	4,162.2	3,577.9	26.3	110.5	0	194.4	8,299	1829-2006
Brown Coal (raw)	Mt	2,061	-	-	-	-	-	-	2,061	1889-2006
Copper	kt	15.4	2,590	10,402	1,677	2,802	367	848	18,732	1842-2006
Diamonds	Mcarats	-	~0.2	-	-	-	~0.52	~730.0	~731	1867-2006
Gold	t	2,377.4	819.0	1,336.6	196.2	55.8	514.4	6,021.4	11,321	1851-2006
Ilmenite	kt conc	102	~1,104 [#]	~4,116 [#]	0.6	1	-	~39,570 [#]	~59,999	1934-2006
Iron Ore	Mt	0.041	4.843	0.668	76.75	236.9	6,884	4,386.5	4,713	1889-2006
Lead	kt	0.4	22,478	~10,632 [#]	2,220	18.1	569.5	760.9	~36,453	1850-2006
Manganese Ore	kt	0.44	76.4	158.4	0.76	62.7	63,354	8,238	71,890	1946-2006
Monazite	kt	0	~22 [#]	~5.5 [#]	0	0	0	~220	~251	1947-2006
Nickel	kt	0	0	327.4	~0.6	0	0	~3,267 [#]	~3,594	1967-2006
Rutile	kt conc	66.8	~4,643 [#]	~4,194 [#]	39.8	1.7	-	2,951	11,897	1934-2006
Synthetic Rutile [§]	kt	-	-	-	-	-	-	»8,530	»8,530	1934-2005 [§]
Silver	t	~55	~33,942	~32,066	~5,573	~288	~799	~1,911	~75,618	1870-2006
Tin	kt	13.68	~182.3	~176.1	~392.3	<0.1	6.0	~37.7	~800	1870-2006
Uranium	t U ₃ O ₈	0	0	8,893	0	50,466	105,209	~11.5	164,580	1906-2006
Zircon	kt	20.8	~4,819 [#]	~3,317 [#]	38.5	0.37	<0.5	10,557	~18,588	1934-2006
Zinc	kt	~19.5	~22,694 [#]	~12,212 [#]	~5,351 [#]	415	~2,062	2,667	~45,489	1883-2006

[#] / ~ Data incomplete / approximate; » Much greater than. ^P 2005 production data is preliminary only. [§] Synthetic rutile data for WA only from 1980 (production started in the late 1960's).
All data sources listed in detail in appendix, with state and Australian totals being approximate only and based on the best available data set.

The available data compiled for open cut mining, based on the proportion of ore, is shown in Figure 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). Overall, for most minerals shown, there is a general trend towards increasing open cut mining with only minor exceptions. Many minerals are not shown as they have always been completely extracted by open cut mining (eg. 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 Mt Lyell and Mt Morgan, the start of Mt Isa, and the development of major open cut copper mines in the past decade (eg. Ernest Henry, Cadia, Nifty). Similarly for uranium, the switch from open cut to underground mining is due to the sheer scale of Olympic Dam. A critical mineral to note is black coal, which has moved from complete underground mining to about 80% open cut mining over the same period which has seen exponential growth in coal mining and exports (including brown coal brings this shift forward by about two decades).

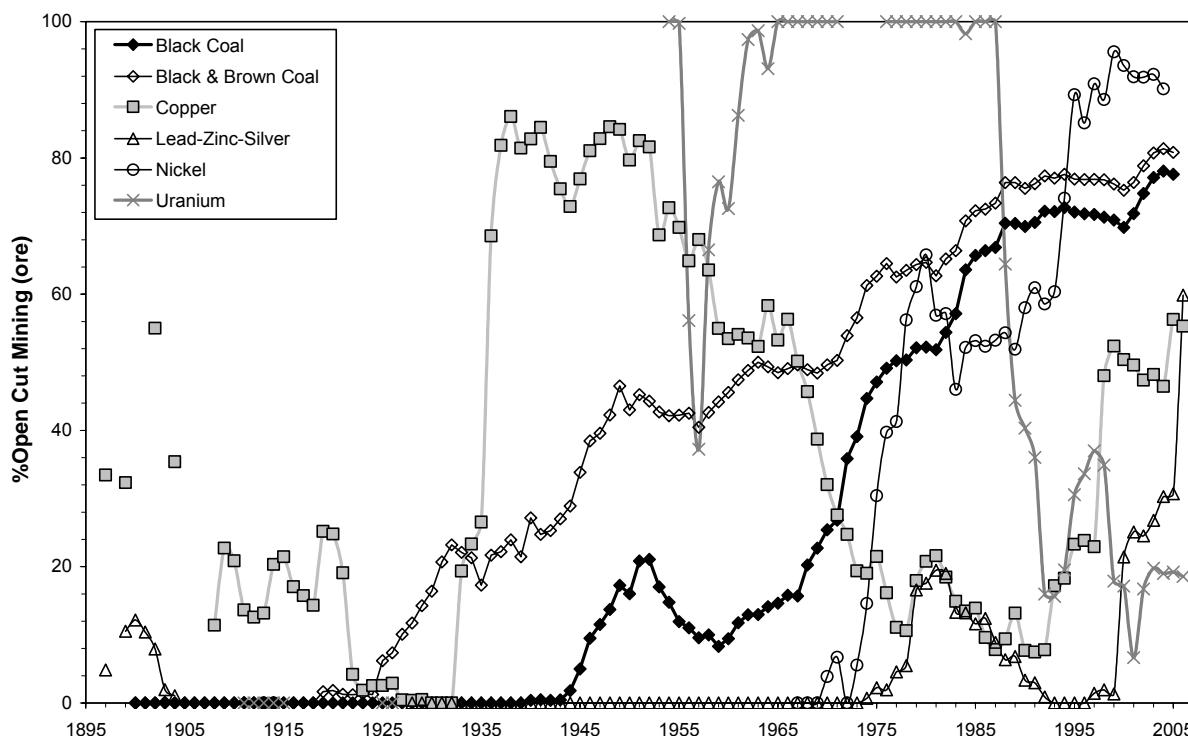


Figure 4. Historical trends in open cut mining in Australia (%ore basis) (adapted from Mudd, 2007a)

The available data compiled for waste rock (or overburden), primarily from open cut mining, is shown in Figure 5. The changes over time are related to the start and finish of major open cut mines (eg. Mt Lyell and Mt Morgan for copper, Argyle for diamonds, the 1980s gold mining boom), but just as critical is the rapid evolution in bulk earth moving technology and scale since about 1950. For example, the development of ammonium nitrate fuel oil (ANFO) explosive technology in the 1960s was also critical for the continuing expansion of open cut mining, due to ANFO's cost and safety advantages (O'Malley, 1988; Oliver, 1979). Over time it can be seen that for most minerals there is a major shift to open cut mining, as it commonly allows for more complete and economic extraction of a deposit.

Associated with this move to open cut mining is the ratio of waste rock (or overburden) to the ore mined, shown in Figure 6. For some minerals, there is a gradually rising ratio over time (eg. black coal, gold, copper) while for others it is relatively stable (eg. brown coal). It should be noted that the data presented in Figures 5 and 6 is a minimum only, since not all companies report waste rock / overburden. For the data compiled, no year represents all waste rock / overburden due to gaps from some open cut mines, while data from underground mines is extremely rare. It is therefore not possible to compare waste rock-ore ratios between open cut and underground mines.

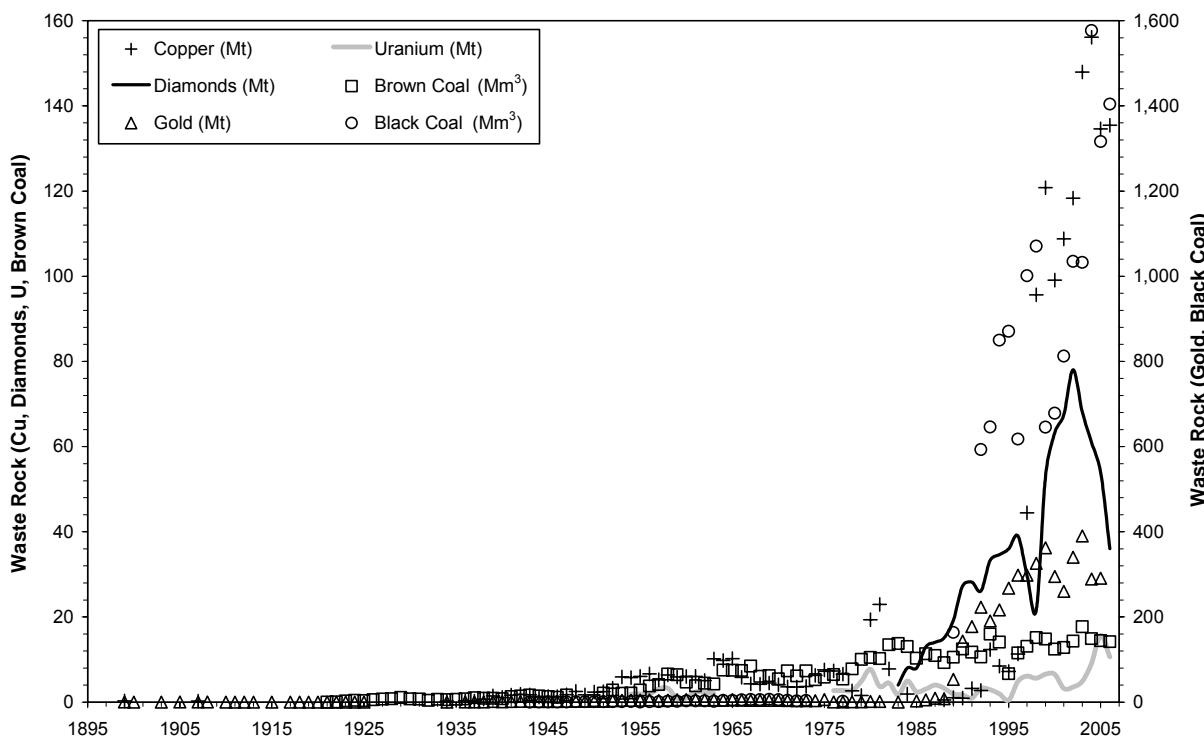


Figure 5. Historical trends for waste rock and overburden in Australia (adapted from Mudd, 2007a)

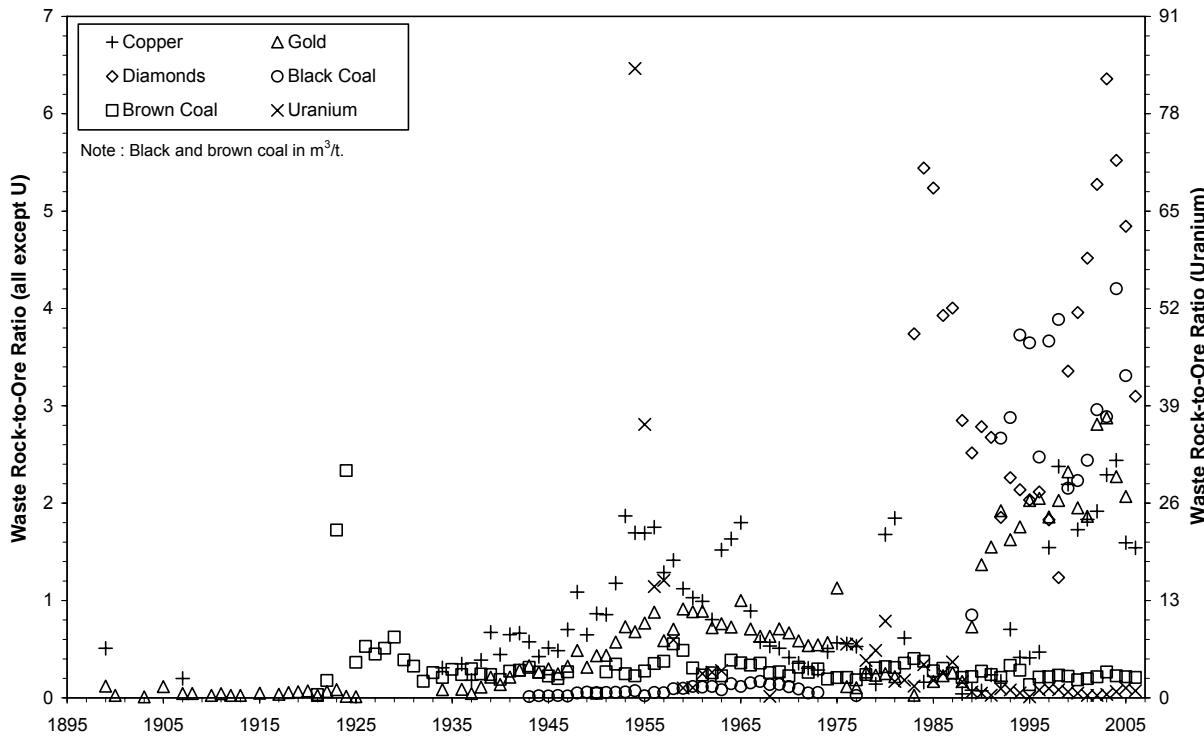


Figure 6. Historical trends for waste rock-to-ore ratios in Australia (adapted from Mudd, 2007a)

The available data for economic mineral resources over time is shown in Figure 7. Data from 1975 onwards is derived from GA (2006) while earlier data is compiled from BMR (various) or other sources (see Mudd, 2007a). 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 1950s-60s mining boom is clearly visible, with other minerals showing increasing or stable trends.

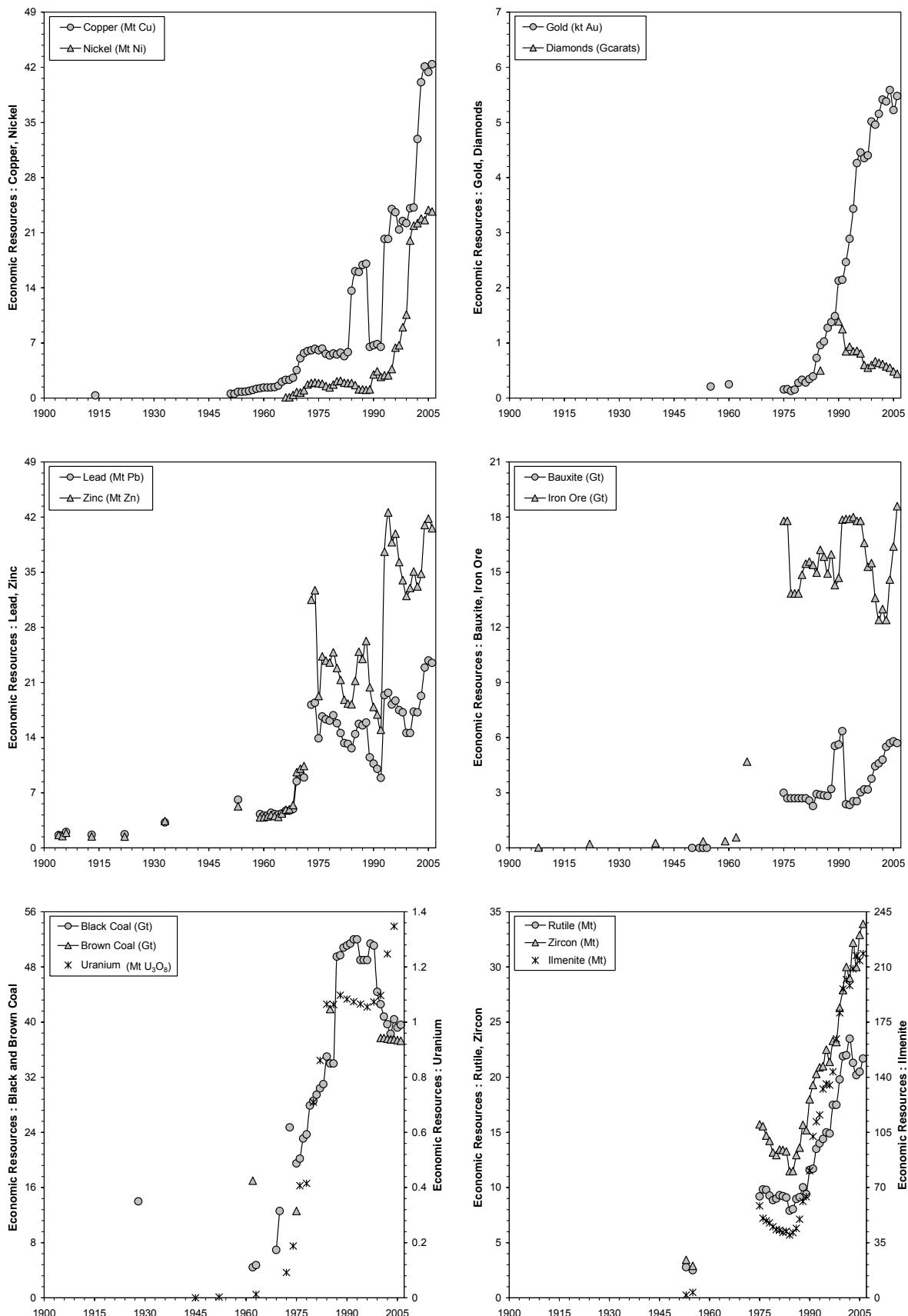


Figure 7. Historical trends for economic mineral resources in Australia (adapted from Mudd, 2007a)

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 2005 production and ignores increasing annual production over time.

Table 2. Economic Resources, Production and Years Remaining (2005) (Mudd, 2007a)

Mineral	Production	Economic Resources	Years Remaining	Sub-Economic Resources [§]
Bauxite	59.96 Mt	5,800 Mt	97 years	3,200 Mt
Black Coal	~398 Mt	39,200 Mt	99 years	67,900 Mt
Brown Coal	67.15 Mt	37,400 Mt	557 years	156,100 Mt
Copper	918 kt	41.4 Mt	45 years	36.4 Mt
Diamonds	30.65 Mcarats	493 Mcarats	16 years	-
Gold	262.98 t	5,225 t	16.8 years	5,836 t
Ilmenite	~1.88 Mt	214 Mt	114 years	170.4 Mt
Iron Ore	~261.7 Mt	16,400 Mt	63 years	20,800 Mt
Manganese Ore	~3.60 Mt	143 Mt	~40 years	345 Mt
Lead	767 kt	23.8 Mt	31 years	33.8 Mt
Nickel	187 kt	22.6 Mt	121 years	23.7 Mt
Rutile	177 kt	20.5 Mt	116 years	42.1 Mt
Uranium	11.25 kt	1.35 Mt	120 years	-
Zinc	1,367 kt	41.8 Mt	31 years	47.3 Mt
Zircon	426 kt	32.9 Mt	77 years	50.3 Mt

[§] includes para-marginal, sub-marginal and inferred resources from GA (2006); diamond resources from company reports while uranium is from OECD-NEA & IAEA (2006).

5 Results : Sustainability Reporting and Resource Intensity

5.1 Energy Consumption – Uranium and Gold Mining

The compiled data sets for the energy intensity (cost) of gold and uranium mining is shown in Figure 8, based on data sets in Mudd (2007b,c) and Mudd & Diesendorf (2007). Average energy intensity for gold and uranium production is summarised in Table 3. For uranium, Olympic Dam is presented at 100% and 20% to account for the fact it is a copper-uranium project, with 100% assuming no copper production (a reasonable assumption since the ore grade is similar to the Rössing uranium mine) or 20% being the average proportion of revenue received from uranium over time. More accurate energy accounting for uranium production at Olympic Dam is not possible without detailed mining and process data and specific energy allocations to respective process/metallurgical segments.

5.2 Cyanide Consumption – Gold Mining

The compiled data set for the cyanide intensity (cost) of gold mining is shown in Figure 9, based on Mudd (2007b,c). Average cyanide intensity for gold production is summarised in Table 3.

5.3 Water Consumption – Uranium and Gold Mining

The compiled data set for the water intensity (cost) of gold and uranium mining is shown in Figure 10, based on data sets in Mudd (2007b,c) and Mudd & Diesendorf (2007). Average water intensity for gold and uranium production is summarised in Table 3. The Olympic Dam project is analysed in the same way as energy. All water is adopted as it is presented in sustainability reports (see discussion).

5.4 Greenhouse Emissions – Uranium and Gold Mining

The compiled data set for the greenhouse intensity (cost) of gold and uranium mining is shown in Figure 11, based on data sets in Mudd (2007b,c) and Mudd & Diesendorf (2007). Average greenhouse intensity for gold and uranium production is summarised in Table 3. The Olympic Dam project is analysed in the same way as energy.

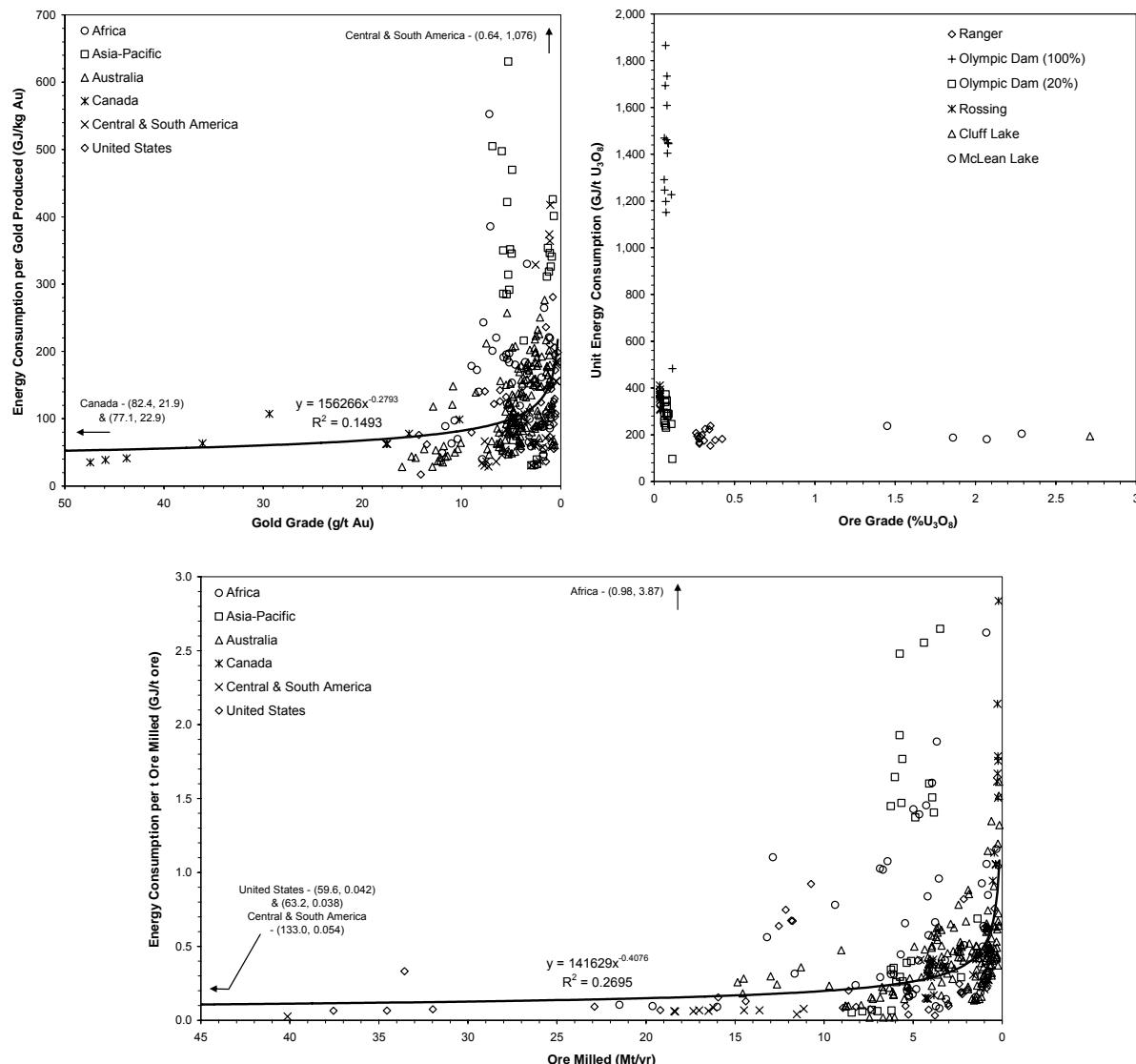


Figure 8. Energy Costs for Gold (left) and Uranium (right) Production : (top) with respect to ore grade; (bottom) energy costs of gold with respect to ore throughput

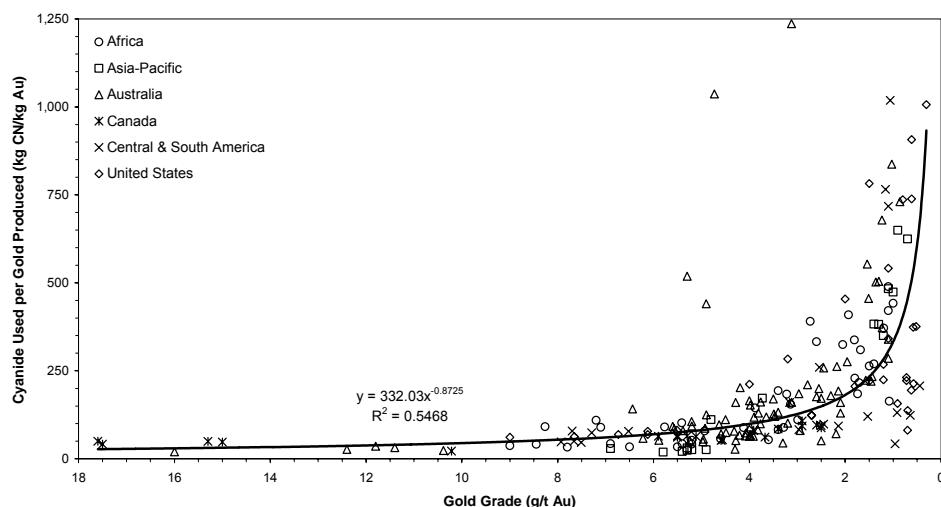


Figure 9. Cyanide Cost for Gold Production (with respect to ore grade)

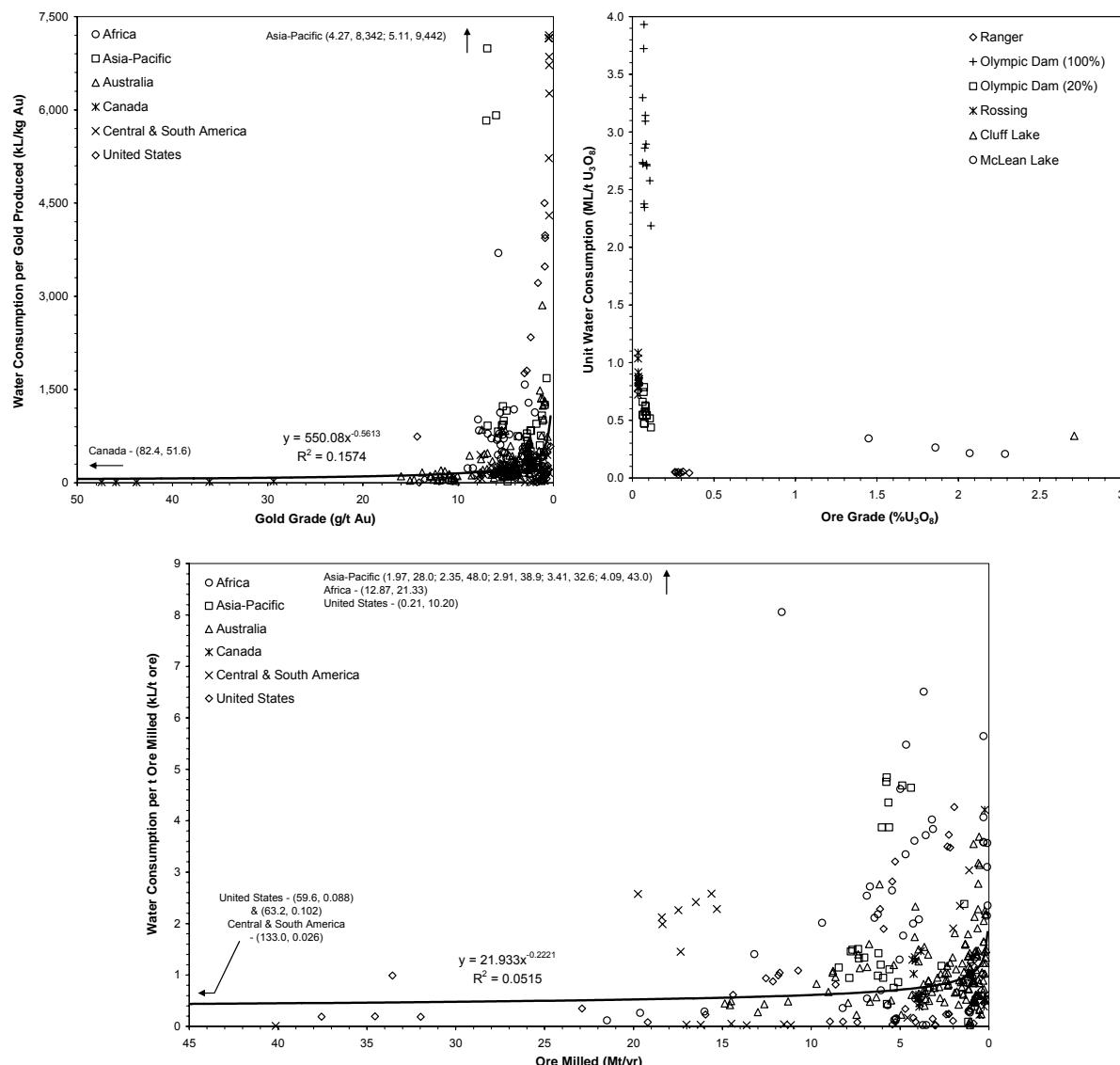


Figure 10. Water Costs for Gold (left) and Uranium (right) Production : (top row) with respect to ore grade; (bottom row) with respect to ore throughput (gold only)

Table 3. Average Resource Intensity for Gold and Uranium Production

	Energy Consumption	Water Consumption	Greenhouse Emissions	Other
Gold	143 GJ/kg Au	691,000 L/kg Au	11.5 t CO ₂ -e/kg Au	141 kg cyanide/kg Au
Uranium [†]	222 GJ/t U ₃ O ₈	414,000 L/t U ₃ O ₈	27.4 t CO ₂ -e/t U ₃ O ₈	-

[†] Based on weighted average of all mines.

6 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. This discussion will be succinct, with additional discussion and analysis in Mudd (2007a,b,c) and Mudd & Diesendorf (2007).

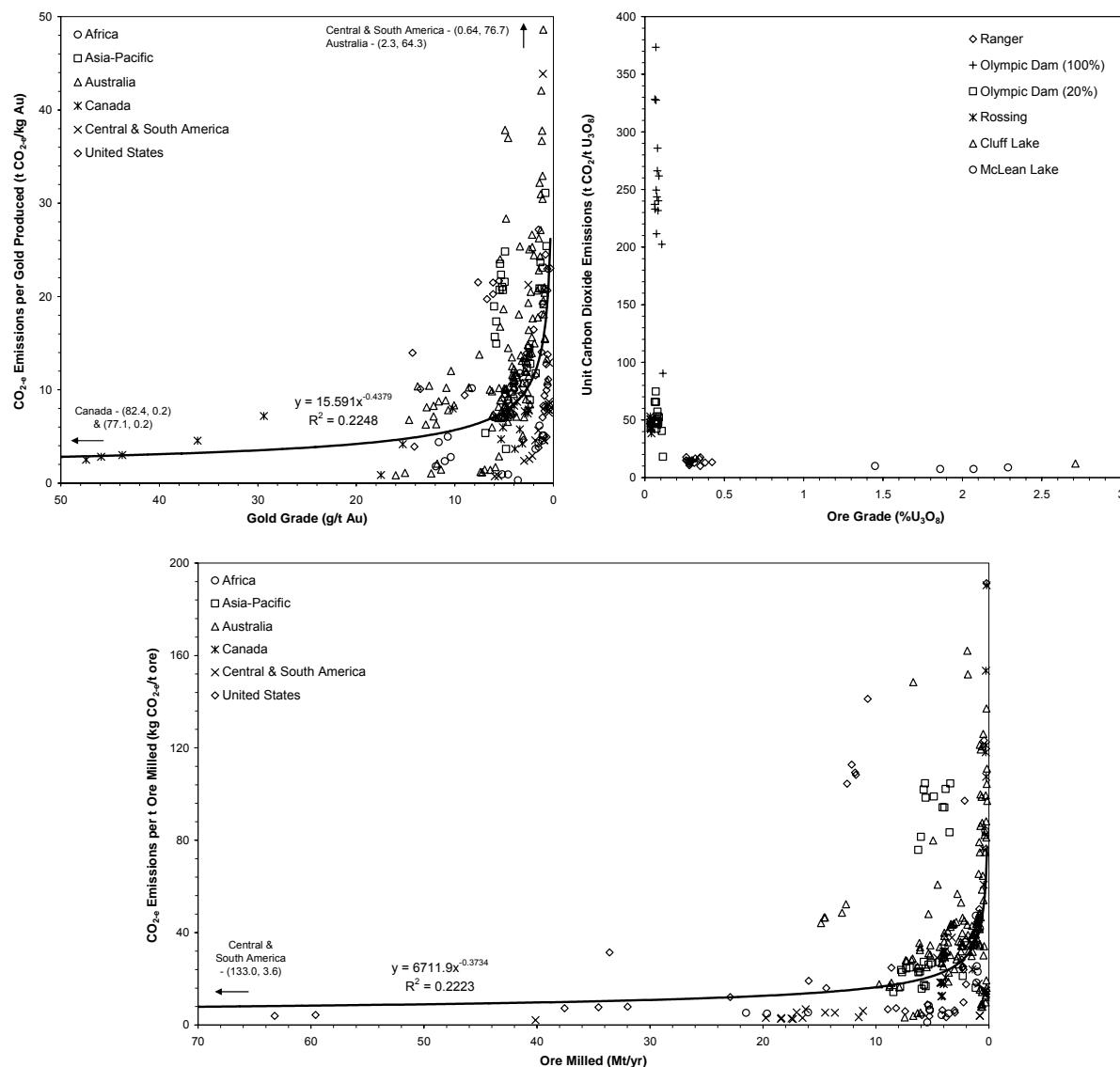


Figure 11. Greenhouse Costs for Gold (left) and Uranium (right) Production : (top row) with respect to ore grade; (bottom row) with respect to ore throughput (gold only)

6.1 Fundamental Trends in Mining : Production, Ore Grades and Resources

For almost all minerals in Australia, production continues to gradually grow over time, with some exponentially (eg. copper, black coal, zinc, iron ore). Depending on the mineral, there are various reasons for this production growth, commonly being new discoveries (and mines), expansions, new technology or evolving economics and market demand. The current so-called 'super-cycle' in global mining is causing a new phase of strong and near-exponential production growth for many minerals.

For most metallic minerals there are long-term declines in average ore grades processed – and this could be terminal when combined with increasing production. Some trends show the influence of mines being expanded, exhausted or opened, the best example being copper (such as Burra, Mt Lyell, Mt Isa and recent mines). For most minerals, based on known deposits, it is hard to envisage new discoveries or mining techniques ever leading to ore grades rising in the future. Further to this, known deposits suggest that ore grades will continue to decline, perhaps at a slower rate than the past. According to Mudd (2007a), the average gold ore grade processed in 2005 was ~1.94 g/t whereas a compilation of economic gold resources for 2005 shows a grade of ~1.0 g/t. Two other principal issues related to ore grade is impurities (eg. arsenic) and the quality or refractory nature of the mineralogy (eg. over time more refractory lead-zinc-silver deposits have been developed (Mudd, 2007a,d).

The principal mining technique has, since about 1950, moved from underground mining to be dominated by open cut mining, 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 and Weipa. For select minerals, 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 (overburden) extracted annually in the Australian mining industry. The dominance of open cut mining looks set to continue for the foreseeable decades, provided the price of transport fuels remains competitive (i.e. diesel). For some metals, such as copper and gold, 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 potential Mt Isa pits).

In conjunction with the major shift to open cut mining, the extent of waste rock (and overburden) is now likely to be at least equivalent to the amount of ore mined and for many minerals is likely to be two times higher or more (eg. gold, black coal, iron ore, copper). While a major proportion of this waste rock is likely to be somewhat 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. At present, there is no requirement for public reporting of the extent of waste rock mined annually, nor the nature of excavated waste rock (such as potentially acid-forming).

The rehabilitation of mined land and associated mine wastes is now a major legal requirement as well as 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 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 East Finniss River is still heavily polluted by acid mine drainage leaching from **rehabilitated** waste rock dumps, shown below in Figure 12. Caution clearly needs to be applied in this area.



Figure 12. White's waste rock dump, Rum Jungle, July 2007, ~25 years after rehabilitation : (left) White's waste rock dump and acid mine drainage, (right) adjacent East Finniss River during the dry season (no flow) showing the cumulative effects of acid mine drainage. (photos – author)

With respect to economic resources, most commodities show gradually increasing quantities, with distinct periods of major increases evident at different times for particular minerals (eg. 1960s for iron ore, 1980s onwards for gold, 1990s onwards for rutile and zircon). For copper, major new discoveries continue to be made (eg. Prominent Hill and Carrapateena in South Australia) as well as brownfield increases to existing deposits or mines (especially Olympic Dam and Mt Isa). Nickel resources increased substantially in the 1990s due to the inclusion of nickel laterite resources as economic due to the emergence of new process technology (Mudd, 2007d). In comparison, uranium has increased over time due to increased drilling and expansion at known deposits (principally Olympic Dam, plus Ranger to a lesser extent) rather than new deposits being discovered. The recent resurgence in uranium exploration may lead to new deposits in the near future, though they are likely to be deeper and therefore more difficult to find than past era's of effort.

According to GA (2006), it "is notable that resources levels for major commodities like black coal, iron ore and base metals have plateaued" (pp 10). For black coal, however, the amount of 'economic resources' is commonly only that existing in current mine leases and has had sufficient mine planning to classify it as mineral resources under the Joint Ore Reserves Committee code ('JORC') (see AusIMM et al., 2004; CGCNSW & QMC, 2001). 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, 2007a) – a value one order of magnitude higher than the Geoscience Australia 2006 estimate of 39.6 Gt. Similarly, Mudd (2007a) compiled data to demonstrate that the same basis exists for brown coal, iron ore and bauxite. For metallic commodities, such as copper, nickel and gold, sustained rises in economic resources have 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 also demonstrated in Table 2, with sub-economic resources commonly being at least the same as or higher than economic resources.

The fundamental issue which follows from this is not whether mineral resources are 'finite' but the future conditions under which mineral resources are likely to be considered 'economic' and the associated social and environmental costs of mineral production. The emergence of sustainability reporting and associated data affords the opportunity to analyse this issue more thoroughly.

6.2 Sustainability Reporting and Mining : Comprehensiveness and Transparency

The data presented on sustainability reporting, and estimates of the resource intensity per unit mineral production demonstrate that resource intensity is sensitive to the ore grade being processed for gold and uranium. This could be expected intuitively, as lower ore grade requires more ore to be mined and processed for a given level of production. The data suggests that larger projects can achieve economies of scale. The compilations presented on gold and uranium mining were effectively industry level views, with aspects such as open cut or underground mining, heap leaching versus carbon-in-pulp milling, tropical, temperate or arid climates, etc, not included as potential factors (commonly due to lack of reporting or sufficient details). A review of the compiled data does not suggest or indicate the degree to which these factors could influence the resource intensity for gold or uranium production. At present, further research and analysis is required to understand the extent to which these factors influence the resource intensity of a given mine and mineral product. When the ore grade sensitivity of resource intensity is considered in light of declining ore grades, and potentially increasingly refractory ores, it would appear that the resource intensity of mineral production in the future will increase given existing technology.

In terms of sustainability reporting, there are a number of issues which are apparent with respect to the Global Reporting Initiative and the National Pollutant Inventory (NPI) (NPI, 2001).

Under the current third edition of the GRI protocol (GRI, 2006) and the additional mining sector supplement (GRI, 2005), the primary indicator for solid mine wastes is 'EN22', which is the "total weight of waste by type and disposal method". It clearly includes wastes such as landfill (putrescible material), metal scraps, inert solids (eg. cement), construction waste, solid chemical wastes, used tyres, and the like. There is widespread inconsistency, however, in whether EN22 explicitly includes solid wastes such as tailings, waste rock and overburden. The mining sector supplement goes on to state that "large volume wastes" – i.e. tailings and waste rock – should be reported after a site-specific risk assessment (pp 29, GRI, 2005). 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. To illustrate this, two examples of solid waste reporting under EN22 are shown in Figure 13, and highlight the variable way in which data is reported. In both cases 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. Furthermore, while some companies do acknowledge and discuss the nature of their solid wastes, such as potentially acid-forming, but quantitative data in sustainability reports is exceedingly rare – the vast majority of companies do not discuss such issues. At present, significant further research is needed to fully characterise the extent and nature of tailings, waste rock and overburden, and especially the long-term success of rehabilitation measures on more reactive mine wastes.

ENVIRONMENTAL		2005	2004	2003	2002	2001
Mineral Waste Management (Includes destination of Tailings / Waste Rock) (Million Tons)						
Input-Backfill					54.15	
Underground						
Tailings Dam						
Sub-Sea						
Rock Dumps					12.58	
Stockpiles						
Other (e.g., used as road base, construction material)						
Overburden, tailings and slag	tonnes	47,000,000	17,000,000	42,000,000	49,000,000	25,000,000

Figure 13. Two examples of tailings and waste rock reporting under GRI's solid waste indicator (EN22)

Other critical aspects of sustainability data include energy, water and chemical inputs and greenhouse emissions, amongst others. The respective GRI indicators for these aspects are (examples added) :

- **Direct Energy (EN3, core)** – direct energy consumption by primary energy (eg. fossil fuels);
- **Indirect Energy (EN4, core)** – indirect energy consumption by primary energy (eg. coal-fired electricity);
- **Energy Efficiency (EN5-7, additional)** – primary energy saved due to efficiency and/or conservation, energy conservation initiatives;
- **Water (EN8, core)** – total water withdrawal by source (eg. groundwater, surface water);
- **Water Withdrawal Impacts (EN9, additional)** – water resources impacted by withdrawal (eg. wetlands);
- **Water Recycling (EN10, additional)** – percentage and total volume of water recycled and reused (eg. process water, grey water);
- **Water (EN21, core)** – total water discharges by quality and destination (eg. rivers, marine waters);
- **Significant Spills (EN23, core)** – total volume of significant spills (eg. pipeline leak);
- **Greenhouse Emissions (EN16, core)** – total direct and indirect greenhouse emissions (eg. gas, electricity);
- **Material Inputs (EN1, core)** – input materials used by weight or volume (eg. cyanide);

At present, there is no consistency on the reporting of most of the above sustainability metrics.

For energy, some reports give totals only and no explanation of energy sources or split between direct and indirect energy, while other companies give detailed breakdown by several energy sources (eg. diesel, petrol, kerosene, natural gas, electricity). 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). For more comprehensive analyses of the energy costs for mineral production, especially linking greenhouse costs, it is imperative that complete data by direct and indirect energy source be provided in consistent units (eg. GJ).

Similarly for greenhouse emissions, complete data is 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).

With respect to water, there is 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 water costs or "embodied water" (Mudd, 2007e).

A critical issue for water resources which is not included in GRI indicators is that of the water 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. For example, numerous mines in arid central Western Australia utilise hyper-saline water resources (commonly groundwater and, to a lesser extent, also surface waters) with a salinity higher than seawater (see McCowan & White, 1993; Norgate & Lovel, 2006; Sparrow & Woodcock, 1993).

The varying quality of water resources used for different mines makes the equivalent water costs a vexed issue to estimate. The inconsistencies in reporting total and recycled water consumed in mineral production, as well as the varying quality of water resources, could help to explain the scatter and variation in the three graphs in Figure 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. 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 clearly remains critical to consider these combined and often cumulative effects in any assessment of the sustainability and water in mining.

Additionally, many mines or companies reporting energy, greenhouse, water and cyanide data over time and fail to explain sudden abrupt increases or reductions in any of these aspects. For example, one gold mine reported a change in total greenhouse emissions from 0.18 to 1.1 Mt CO_{2-e}/yr despite no new mine or other significant change in the project's configuration. This is sometimes related to corporate takeovers or merger activity leading to new policies or methodologies for assessing sustainability data, but this is rarely explained in subsequent reports. Some mine sites report substantive changes but provide no explanation at all. Alternately, some company reports do not report certain aspects. For example, some companies report cyanide consumption but not greenhouse emissions, while the reverse applies for other companies – sometimes despite both companies basing their reporting framework on the GRI framework.

Finally, some companies choose to report corporate totals only under GRI and not site-specific data, making more comprehensive analyses impossible.

As a voluntary protocol, the GRI is clearly helping to improve the breadth and depth and consistency of sustainability reporting, but there remains many areas in which mining companies can substantively improve their sustainability reporting.

In Australia, the National Pollutant Inventory (NPI) only considers 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 to the NPI). This is a critical weakness in the NPI accounts, as both tailings and waste rock have the potential to become major point sources of listed pollutants such as cyanide and various metals (eg. Sb, As, B, Cd, Cr, Co, Cu, Pb, Mn, Hg, Ni, Se, Zn). A simple search of the facilities in the databases via the NPI website (www.npi.gov.au) reveals that some major sites of acid mine drainage (eg. Mt Lyell, Tasmania) are included in the facilities reporting under the NPI, while others are not (eg. Mt Morgan, Queensland). Given the vast quantities of mine wastes now produced annually in Australia, there would be a very substantive quantity of listed NPI pollutants contained within tailings and waste rock yet they are excluded from, or least poorly addressed by, such accounting and reporting systems.

Based on the results presented on sustainability reporting and estimated resource intensity, there is still room for significant improvement in disclosure by mining companies in sustainability reports.

7 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 sustainability of mining, 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 :

- **Exponentially increasing production** – almost all minerals and metals show strong growth over time, especially over the past three decades;
- **Declining ore grades (or quality)** – while early mines processed rich ores, average industry grades for most metals and minerals are now commonly 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 there has been a major shift in mining technique from underground to open cut mining, especially in some sectors such as coal, gold and nickel;
- **Waste rock / overburden** – combined with the increase in open cut mining, there has been an exponential increase in the waste rock or overburden excavated in modern mining. For most metals and minerals the quantity of waste rock / overburden excavated is significantly higher than the ore processed or product mined, and this ratio is increasing over time – presenting a major 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 many 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;
- **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, and 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. This makes comprehensive sustainability reporting even more critical.

This paper has presented a range of data sets on the sustainability of the modern mining industry as well as various issues affecting the resource intensity or environmental costs 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 we may be able to continue to find new mineral deposits in the near future, improve technology or favourable economics will facilitate 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. In summary, the vast scale of modern mine waste and its existing and future resource intensity will continue to challenge the sustainability of the modern mining industry and requires eternal vigilance by all involved – regulators, shareholders, governments and communities alike.

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